AUTOMATIC

GAIN CONTROL

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for a

BROADCAST AMPLIFIER

By

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Introduction.

It has been estimated[1] that when the Philadelphia Symphony Orchestra of some hundred odd pieces plays Bach's "Toccata and Fugue in D Minor", there is between the loudest burst of music from full orchestra and the softest note of the gentle flute a volume range of 70 decibels. Experiments[2] have shown that when a radio receiver is operated in the home under average conditions, the range between the loudest comfortable listening level and the lowest volume sufficient to overcome background noise of both the room and the receiver is forty decibels. Between the input to the microphone and the output of the receiving set then, there must exist some agency to contract the larger range to within the limits of the smaller. This 'agency' is ordinarily the control operator and it is among his responsibilities to so set his main gain control that the loudest notes will just modulate the transmitter to its capacity, and then vary his controls more or less continuously to contract the volume range the necessary amount. It is this latter operation which might profitably lend itself to automatic or semi-automatic control.

It is quite true comparatively few programs will show the full seventy decibel variation; but some controlling is always necessary on any program - except perhaps that of a modern dance orchestra. Moreover it is only under ideal conditions that the forty decibel range can be tolerated. The working range of a transmitter of a

1. The Reproduction of Orchestral Music in Auditory Perspective, Bell Lab. Record, Vol. 11, No. 9, May, 1933.

2. Communication and Broadcast Engineering.

given power rating is a function of its average percentage modulation and a station which is broadcasting a program having a forty decibel range, the peak signals of which modulate the transmitter to 90% will have an average modulation of only 10 or 15%. The result is that except for favorable locations near the transmitter the softer portions of the music will not be sufficiently far above the atmospheric noise level to make reception worth while. Again, at the receiving end, there are comparatively few listeners who operate their sets so that the peak signals reach the loudest comfortable listening level. Whether or not it be right, the general tendency is to have the radio on at rather low volume, so that ordinary conversation can still be carried on above the program. A 40 decibel variation under these conditions would mean the complete inaudibility of the softer passages. For these reasons it has been found necessary to contract the range still further and practice dictates a permissable variation of 30 decibels.

Although the problem of automatic control has been recognized in the broadcast field[1] the chief attacks upon it have been made in the field of long distance telephony. A device known as the 'compandor'[2] (compressor-expandor) has been developed for use in the transatlantic long wave radio telephone circuit between London and New York. Its function is to compress the range of the signal variations at the trans-

1. Stuart Ballantyne, "High Quality Broadcasting", Proc. I.R.E., p. 571; 1934.

2. R.C. Mathes and S.B. Wright, "The Compandor", B.T.S. Monograph B-798: June 1934.

mitting end and expand the condensed range back to its normal value at the receiving end. The principle of operation is interesting: the plate resistance of two tubes connected in push-pull is made the shunt arm of an H type network, and this "losser" network is inserted at the input to the amplifier. The plate resistance of the push-pull tubes is a function of their grid bias and by causing this grid bias to vary with the amplitude of the signal envelope at the amplifier input, it is possible to automatically control the amount of loss introduced. Fig. 1 shows a rough schematic diagram of the compressor.

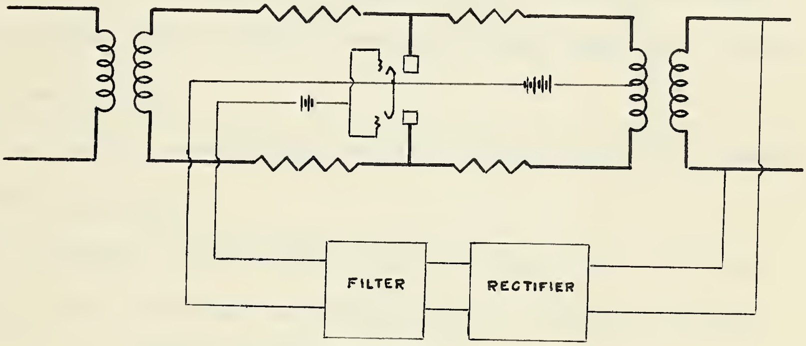


FIG. 1

In the broadcast field there has been developed[1] a semi-mechanical control which is actuated by the number of peaks per second exceeding a predetermined limit. It uses a system of re-

1. Stuart Ballantyne; Loc. cit. Page 571.

lays to cut resistance pads into the input circuit, reducing the input to the amplifier in 2 D.B. steps until the number of excessive peaks per second is below the limit established by the apparatus. This device serves to back up the control operator in his judgment and acts as a safety valve. It has the disadvantage however of being 'a posteriori' in its action, a certain number of overload peaks having to occur before the control will act.

It was the fourfold purpose of this investigation

(1) to determine the possibility of adopting the simple automatic volume control of receiving sets to an audio amplifier and utilize this action to work as a safety device on overload peaks.

(2) to build such a control for an existing transformer coupled studio amplifier.

(3) to attempt a continuous control action rather than a mere safety valve on peaks.

(4) if possible, to show the action of the control oscillographically and so determine what distortion it might introduce.

General Considerations

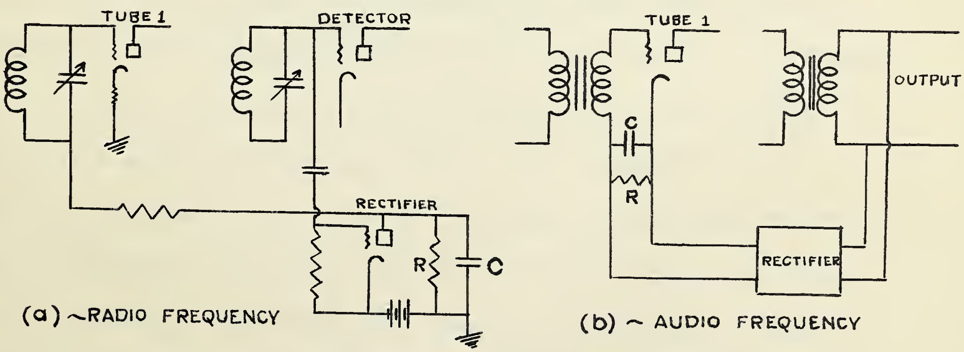


FIG. 2 ~ A.V.C. CIRCUITS

The theoretical a.v.c. circuit of receiving sets as applied to the radio frequency stages is shown in fig. 2(a), while developed from it for an audio amplifier is the circuit of 2(b). The signal is fed through tube 1 and the remainder of the amplifier, and appears in amplified form at the detector or amplifier output as the case maybe. Here a portion of the energy is used to feed a rectifier, the output of which, after suitable filtering by the low pass filter circuit (C,R), is applied to the grid of the variable-mu tube (tube 1). If the connections are correct an increase in signal will produce a larger voltage drop across R and increase the bias on tube 1, thus reducing its amplification by an amount that depends on the signal strength. An automatic control is thus accomplished.

There are however several general requirements that such a control must meet before it can be considered satisfactory for the use proposed. These maybe assembled under the term - 'naturalness of reproduction'. This involved the consideration of such factors as: The time constant of the control, that is speed with which the control acts in reducing or increasing the volume; the effect on background noise during in-between periods of no music; the 'power' of the control, being the decibels reduction due to the control for a given number of decibels output; the 'intensity' of the control, indicated by the slope of the input-output curve with the control operative; and the range of the control, being the range in decibels output over which the control is effective. A major factor is freedom from distortion. This might be steady-state distortion such as could occur in any audio amplifier and includes

(a) Frequency distortion,

(b) Amplitude distortion,

(c) Phase distortion,

or it might be transient distortion introduced only while the control is operating to change the volume from one level to another. This latter could be expected to show itself as a change in wave form during actual operation of the control. That is, if a pure sine wave of amplitude A (fig. 3a) is reduced sharply to a similar sine wave (fig. 3b) having amplitude B, what form does the wave shape take between these two points of constant amplitude?

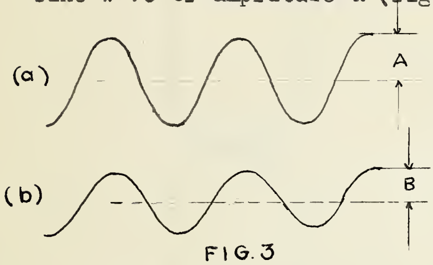


FIG. 3

The Circuit

Fig. 4 is a schematic diagram of the studio amplifier and its associated automatic gain control. The additional equipment required for the control circuit is that shown outside the dotted lines as well as the condenser and resistor C and R. The first stage tube T_1, i.e. the controlled tube, is a variable - mu tetrode replacing the usual triode. $Tr._1$ is a line to grid transformer having a voltage step up of about 11:1. P_1 and P_2 are 200,000 W potentiometers. T_2 is the volume indicator tube and T_3 the automatic control tube, both 112A's. C and R are part of the control circuit but are kept within the amplifier shield (indicated by dotted lines) to maintain short leads in the grid circuit.

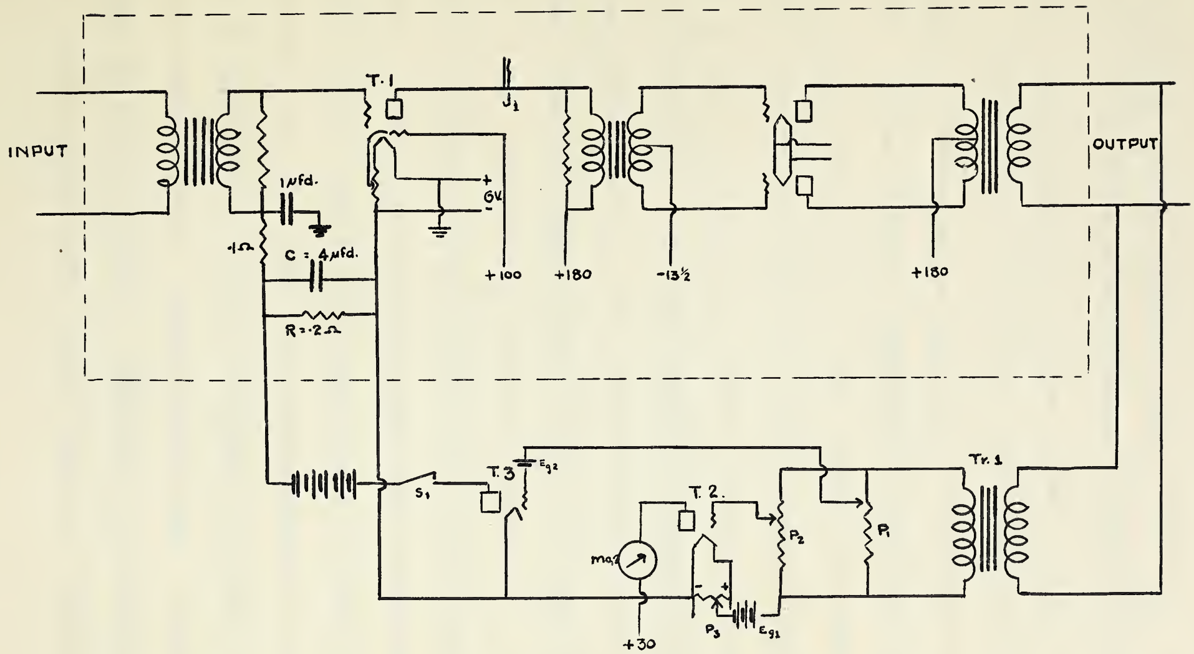


FIG. 4 — AMPLIFIER WITH CONTROL.

Volume indication is accomplished by plate rectification of the signal by tube 2 and allowing this rectified signal to actuate a 0 - 1 milliameter (ma. 2). The no-signal current is determined by the fixed grid bias Eg_1 and the setting of potentiometer P_3. The amplitude of the meter swing for a given signal is adjusted by means of P_2. The control tube T_3 is normally biassed beyond cut-off by Eg_2 and Eg_1 and a variable bias supplied by P_3. The setting of P_1 determines the amplitude of the signal voltage applied to T_3 for a given amplifier output. If the voltage is sufficient to swing the grid of tube T_3 more positive than cut-off a direct current will flow in the plate circuit and a D.C. voltage will appear across R, increasing the bias on the variable-μ tube, and so reducing the amplification factor of that tube. C is large enough to effectively by-pass any audio frequency variations. The output voltage at which the control becomes operative maybe varied by means of P_3 (although it also depends on the setting of P_1) while the setting of P_1 determines the amount of control voltage available for a given output voltage. Switch S_1 provides a convenient means for disconnecting the entire control circuit from the main amplifier and permitting uncontrolled operation. A 0 - 50 panel milliameter inserted in the plate circuit of tube 1 at J_1 serves to indicate the extent of the automatic control action, the D.C. plate current being a function of the bias voltage as shown in graph A. Condenser C and resistance R form the time circuit and upon the rate of charge and discharge of C depends

the speed of action of the control in reducing or increasing the volume.

The operating technique developed with the control was simple. Potentiometer P_3 was adjusted to give a bias of about 1 volt beyond cut-off. (Cut-off bias was indicated when the plate milliameter at J_1 just began to deflect.) With the program passing through the amplifier at normal level, the setting of P_1 was increased until the desired amount of control action was obtained, as indicated by listening tests and observations of the program meter and panel milliameter. Once set, there was no need to change the adjustment of either P_1 or P_3. The manual gain control was then increased about 10 db above its setting with the amplifier uncontrolled. The form of control action obtained maybe understood by an examination of graph B. The curves show the amplifier gain at different outputs for several settings of P_1. They were obtained for a single 1000 cycle note and apply to steady state volume levels only. From them it is seen for example, that with P_1 set at 80 for a power input of - 54 decibels (averaged over say a 1/5 second interval) the output will be - 21 decibels, an amplifier gain of 33 decibels. But if the average power input is increased 10 decibels to - 44 the output is only - 13db, a gain of 31 decibels; while if the power input is increased 20 db to - 34 the output will be - 9 db, an amplifier gain of only 25 decibels. A little experimentation readily determines the optimum settings of P_1 and P_3.

The Controlled Tube.

Several considerations were involved in the selection of the controlled tube. It was important that it be of the variable-mu type and have an amplification as least as great as that of the tube it replaced. Variable-mu tubes, being of the screen grid class, all have high amplification factors but correspondingly large plate resistances so that for them the mutual conductance rather than the amplification factor becomes the figure of merit* of the tube. Fortunately most screen grid tubes have a transconductance at least as high as that of the corresponding triode, though in this particular case the tube being replaced was a 112A, which has the largest transconductance among triodes of the voltage amplifier class. A comparison of tube types available showed the following values for gm**: type 112 = 1700 micromhos, type 58 = 1600 mmhos., type 78 = 1450 mmhos. for Es.g. = 100 and 1650 mmhos. for Es.g. = 125, type 35 = 1100 mmhos., type 39 = 1000 mmhos. The low values for gm ruled

* Terman, pg. 334

$$E = ue_s \cdot \frac{Z_L}{Z_L + R_p} = \frac{u}{R_p} \cdot \frac{Z_L R_p}{Z_L + R_p} \cdot e_s = gm \cdot Zeg.$$

where E is the amplified voltage developed across the load, and $gm = \frac{u}{R_p}$ = transconductance of the tube and

$Zeg. = \frac{Z_L R_p}{Z_L + R_p} = Z_L$ when $R_p \gg Z_L$

For screen grid tubes $R_p \gg Z_L$, ... $\therefore E = gmZ_L$.

**gm = transconductance.

out the latter two at once. Between the 58 and 78, the second has a lower filament drain than the first, being 0.3 amperes at 6.3 volts (which voltage was available) against 1 ampere at 2.5 volts for the 58. However on running the respective Eg - Gm curves, that of the 78 was found to have a sharp break near the working region, viz. at Eg = -1.5 volts. For this reason and because the voltage-dropping resistor required for the filament supply of the 58 afforded a convenient and accurate means of obtaining the fixed bias for the tube, the latter was the one selected.

With any given transformer there is always a particular value of plate resistance that must be used if the amplification is to be maintained constant over a reasonable range of frequencies[1]. This condition ordinarily prevents the interchange of tube types in transformer coupled circuits. However in the case of a triode being replaced by a screen grid tube having a very high plate resistance it can be shown[2] that if a resistor of suitable size be shunted across the primary of the coupling transformer, the frequency distortion with the tetrode will be exactly the same as with the triode. The required value of resistance is that which will make the equivalence resistance of the screen grid tube resistance and the shunting resistor in parallel equal to the plate resistance of the tube replaced. In the present instance the theoretically correct size for the resistor is 5300 ohms. Had the coupling been impedance-capacity

1. Terman, pg. 152.

2. Terman, pg. 339.

the same argument would have applied, while with resistance coupling there would have been no problem of frequency distortion involved.

The Rectifier.

The choice of rectifier was dependent on the conditions of liniarity of rectification, efficiency of rectification, and sufficient amplification of the signal by the rectifier to produce a reasonably large D.C. controlling voltage. The rectifiers in general use in receiving sets are triodes using plate detection, triodes using grid detection, biassed diodes and copper-oxide rectifiers[1]. Of these all except the first form an appreciable load across the circuit to which they are connected and so consume a comparatively large fraction of the signal energy. In the last two mentioned there is no voltage amplification so that unless a large signal output is available an additional stage of amplification is required to furnish sufficient controlling voltage. Grid leak detection gives a greater output voltage for a given input, especially for very weak signals but cannot handle large voltages. Plate detection has the disadvantage of a rather indefinite cut-off point, but this is of little importance when, as is the case, the tube is normally operated beyond cut-off. It has however the advantages of being able to handle large signals such as will be found at the amplifier output, and of pro-

1. Grondahl and Place, Copper Oxide Rectifier used for Radio Detection and A.V.C., Proc. I.R.E., March 1932.

ducing no appreciable load on the line as long as its grid is maintained negative. Moreover in this case it proved particularly easy to incorporate it into a circuit which combined the functions of visual indication of volume and automatic gain control.

The tube selected to function as rectifier was a 112A. It was operated with a plate supply voltage of $22\frac{1}{2}$ V. giving the plate current characteristic shown in graph C. Had a greater controlling voltage been required a type 57 tube could have been used.

The Filter Circuit

Whenever an output ciruit is coupled to its own input circuit there is danger of either regeneration or degeneration, especially for the lower frequencies where the coupling is greatest (assuming capacity coupling). However the double filter used is particularly effective in isolating the grid or input circuit from the output circuit and the percentage of the signal voltage in the plate circuit of the rectifier tube appearing in the grid circuit of tube 1 is very small indeed.*

* This can be shown mathematically using the equivalent circuit: Fig. 5(a) is the exact equivalent circuit of the filter system, while fig. 5(b) is the approximate equivalent circuit at 1000 cycles assuming a 1 volt signal generated in the plate circuit of the rectifier,

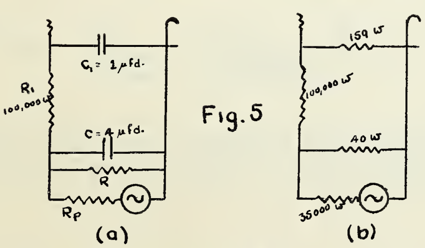


Fig. 5

Voltage across 40 W ------------------ $\frac{40}{35000}$ = .0012 volts

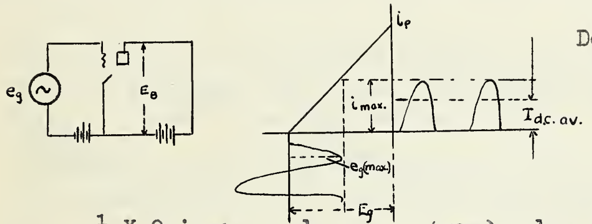
Voltage between grid and cathode ------ $\frac{.0012 \times 159}{100,000}$ = .0000019 = 1.9 microvolts

The Time Constant

There are two different times* involved. One is the time required for the control to reduce the gain on a loud passage; the other is the time taken to increase the gain on a softer passage, after a peak has passed. The first is the time of charging the condenser thro' the average plate resistance R_{Pav}** of the rectifier,

*The time of acting of the control is defined arbitrarily as the time required for the condenser to become charged or discharged to an amount which is $(1 - 1/e) = 2/3$ approx. of its full charge. This follows logically from the fundamental relationship for the discharge of the condenser thro' a resistance, $Q = Q_o e^{-t/CR}$, where Q_o is the initial charge and Q is the charge at time t. Evidently when $t = T = CR$, $Q = Q_o e^{-1} = Q_o/e$. That is the condenser is approximately 2/3 discharged.

**$R_{Pav} \doteq \pi R_p$ for a perfect (straight line) rectifier operated at cut-off. R_p is the A.C. plate resistance of the tube operated as an amplifier. For assume a linear rectifier as shown:



Definition:
$$R_{Pav} = \frac{E_B}{I_{dcav}}$$

$$I_{dcav} = \frac{1}{2} \times \frac{2}{\pi} i\ max. = \frac{1}{\pi} \cdot gm\ eg(max.) = \frac{1}{\pi} \cdot \frac{u}{R_p} \cdot eg. \cancel{\sqrt{2}}$$

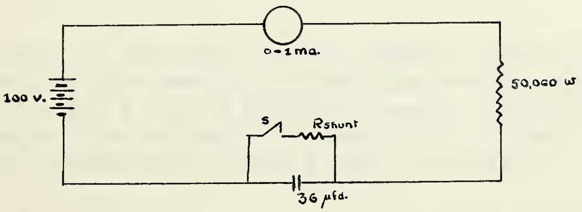
$$\therefore R_{pav} = \frac{E_B}{I_{dcav}} = \frac{\pi E_B}{ueg(max.)} \cdot R_p$$

When $eg(max.) = Eg.$, $R_{Pav} = \pi R_p$

Thus R_{Pav} and therefore the charging time of the condenser is inversely proportional to the amplitude of the rectifier grid swing.

the shunt resistor R having little* effect in this case. With the constants used this time is of the order of 1/10 - 1/5 seconds. This can be calculated approximately from the known value of C and an estimated value of average plate resistance but is shown more readily by the oscillographic records. Thus plate (2b) shows a reduction of 5 D.B. occuring on a 300 cycle note in about 1/6 seconds. It is to be noted that while the contraction is not complete in this time, the major portion has occurred. Plate (2e) shows a much more rapid reduction (t = about 1/30 seconds) obtained by using a 1 mfd. condenser for C. In practice the rapidity with which the control may act is limited by two considerations. The first is that if no new audible frequencies are to be generated by its action, the time should not be less than $\frac{1}{4}$ of the period of the lowest audio note it is desirable to amplify. Arbitrarily taking

*The effect of the resistor shunting the condenser is to reduce the time of charging, the amount of reduction increasing with the ratio $\frac{R_{P_{av}}}{R\ shunt}$. In this case $\frac{R_{P_{av}}}{R\ shunt}$ is small (about 1/10 - 1/5) and the effect of R shunt on the time of charging is also small. This can be readily demonstrated by the following experimental circuit:



this as 30 cycles gives 1/120 of a second. However there is another limiting factor which operates before the above comes into account. That is the maximum decrement per unit time in decibels per second which the ear can tolerate before interpreting the result as a 'cutting-off' or 'throttling' effect. Experiment with the control showed that such an effect* was just perceptible on very large sudden peaks with the time constant resultant with a condenser of about $\frac{1}{2}$ microfarads. Increasing the capacity, and hence the time, to four times this value completely eliminated the effect.

The second time involved, that is the time required to increase the volume after a loud passage has passed, is the discharge time of the condenser C through the resistance R. With the constants shown in figure 4, the time of discharge = C x R = 4 X .2 = .8 seconds. It is this time which is important in determining the naturalness of reproduction. In the tests it was varied from 1/10 to 5 seconds and the value of .8 seconds finally selected, although any time within the range of $\frac{1}{2}$ to 2 seconds is satisfactory. If too short a time is used, say 1/10 second, then the control increases the volume on a soft passage too quickly and some of the artistic effect is destroyed. If a

*The same effect is obtained when the manual control is operated too rapidly. The relative speeds of operation can be compared by studying plates (2 - a,b & e). 'a' shows the manual control operated rather rapidly. 'b' shows the automatic control with a normal time constant while 'e' shows the automatic with a small constant.

very long constant is used, such as 5 seconds, then the gain on being reduced by a loud passage, remains at this lowered level for so long that if these peaks occur at all frequently, the average level of the program will be maintained at too low a value. Paranthetically it maybe stated that this last condition is the one that usually pertains with manual control. If the crescendo is a sharp one and at all unexpected, it is most probable that by the time the operator reaches his control to lower the volume the peak will be passed and the ensuing soft passage will traverse the amplifier at the reduced gain. It takes two or three seconds to determine whether or not the peak is being followed by others. What the experienced operator does of course is to anticipate the music as far as possible and reduce or increase the gain gradually before the volume change actually occurs. Such however is not readily done unless one is well acquainted with the particular selection or provided with the musical score.

It should be noted that the two times can be varied almost independently of each other. Considerable experimentation showed that while there exists a fairly wide latitude in the exact values, the optimum times are about as given.

The Input - Output Curve

The type of control action is made apparent by the shape of the input-output curve. The ideal shape for such a curve is probably that shown in fig. (5). There the control becomes operative at somewhat less than average level and from this point on reduces the gain in proportion to the amplifier output until the maximum output desired is reached. At this point the curve flattens off holding the output constant regardless of input.

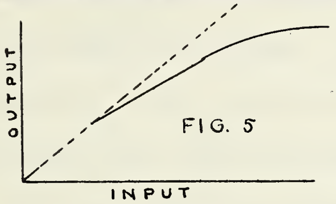


FIG. 5

Quite fortunately this is very nearly the shape of the actual curves obtained with the control as in fig. 4 and as shown by Graph B. However it was felt that for the sake of completeness, the full extent of the various types of controlling obtainable should be shown. It was especially desired to examine the particular case where the input-output curve is a straight line over the major portion of the working range of the amplifier. To realize this condition the rectifier was operated at cut-off and the degree of control action was reduced by means of potentiometer P_1. The first change was designed to extend the range of the control to make it operative at lower values of output volume, while the second was intended to reduce the 'intensity' of control so that the reduction of volume was not too great at the large amplifier outputs.

That such results were at least partially realized is shown by the curves of Graph B which show different degrees of control action

corresponding to various settings of P_1. However on comparing numbers of these, especially some which had been extended into the region beyond the working range, it becomes evident that all of them were decidedly concave downwards at one portion on their range, and that on that part of the curve which was substantially flat, (that is the upper portion), the slopes were very nearly the same regardless of the degree of control. It was thus inferred that these two characteristics of the curves were inherent properties of the control as constructed, and indeed an analysis of the action reveals this to be so. Although a rigorous mathematical solution is not possible, chiefly due to lack of knowledge of the law upon which the Eg - Gm curve of the controlled tube operates, the general case maybe profitably investigated:

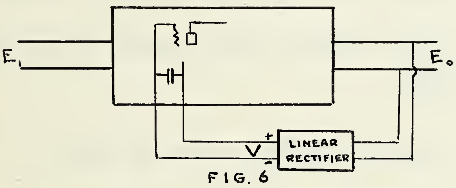


FIG. 6

If in fig. (6) we let

E_1 = input voltage
E_o = output voltage
V = dc. controlling voltage

Then $E_o = K_1 \, f(1/V) \, E_1$ ------------------------(1).

where K_1 is a constant depending on the normal gain of the amplifier, and f(1/V) indicates some function of the control volts V depending on the characteristics of the controlled tube T_1.

Also, $V = K_2 E_o^1$ * ------------------------(2)

if we assume a perfect (linear) rectifier operated at cut-off.

*This is derived as follows: $V = R \times \text{aver. } iP = R \times \frac{1}{2} \times \frac{2}{\pi} \times gm \times eg(max)$

$= K2E_o^1$ if gm is constant

Now if we further assume that

$$f(1/V) = \frac{k}{V^a} \text{ -------------------------(2a)}$$

then (1) becomes

$$E_o = K_1 \frac{k}{V^a} E_1 \text{ -----------------------(3)}$$

Susbtituting for V from (2)

$$E_o = K_1 \frac{k}{(K_2 E_o)^a} E_1 \text{ ---------------------(4)}$$

or

$$E_o^{a+1} = \frac{K_1 k}{K_2{}^a} E_1$$

from which

$$\log_{10} E_o = \frac{1}{a+1} \log \frac{K_1 k}{K_2{}^a} E_1$$

$$= \frac{1}{a+1} \log K E_1 = \frac{1}{a+1} \log E_1 + \log K^{\frac{1}{a+1}} \text{ ----(5)}$$

Now for any given value of a, $\log K^{\frac{1}{a+1}}$ is constant, and

$$\text{Slope of Input-Output Curve} = \frac{\log_{10} E_o}{\log_{10} E_1} = \frac{1}{a+1} \text{ ---------------(6)}$$

That is, when using a linear rectifier the slope of the input-output curve depends only on the value of a, and from equation (2a), a is seen to be the index which determines the amplification of the variable-mu tube at different values of grid bias. That is 'a' is a parameter of the variable-mu tube. An examination of Graph E gives a slight indication of values for 'a' which might be expected. The observed curve shows the amplifier output in decibels, that is

C $\log_{10} E_o$ plotted against the control voltage V. Calculated from this are derived curves showing E_o^2, E_o^1 and $E_o^{\frac{1}{2}}$ as functions of V. None of these curves are linear over the whole range showing that none of the indices chosen will do for values of 1/a. However nearly all the curves are linear over a portion of their range showing that 'a' varies and assumes different values at successive points on the curve. Indeed the inconstancy of the rate of change of curvature of the observed curve gives definite indication of this. However it is to be noted that the curve (a = 1), that is the volts' curve, is fairly linear over the range V = 5 to V = 12, corresponding to reductions of from 6 to 20 D.B.. This gives a slope for the input-output curve of $\frac{1}{2}$ over this range. Checking the actual slope from curve 80, graph B, gives $\frac{10\frac{1}{2}-2}{38-16} = \frac{8\frac{1}{2}}{22} = \underline{.4}$ over the same range.

Examination of equation (5) reveals that the function of the various K's becomes that of shifting this curve from left to right or vice versa, that is, merely varying the magnitude of output voltage at which the control becomes operative.

So far we have assumed a linear rectifier, which condition is approximated in practice with large signals (Graph C). However from equation (4) it is seen that the slope of the input-output curve can be decreased or increased by changing the index of E_o in equation (2). If the rectifier were of the square l~~o~~aw variety and

$$V = K_2 E_o^2$$

then (4) would become

$$E_o = \frac{K_1 k_3 E_1}{(K_2 E_o^2)^a}$$

From which

$$\text{Slope of input-output curve} = \frac{1}{2a + 1}$$

Thus the slope of the input-output curve has been decreased, or the control action has been increased.

If it is desired to reduce the intensity of the control action, a rectifier must be used whose output is proportional to some root of its input. While such devices are not common an approximation maybe obtained by operating the ordinary bias rectifier in the region where the grid will swing positive. Under these conditions the output will bear an approximately linear relationship to the input until the voltage swing is sufficient to cause the rectifier grid to become positive, at which point the putput will fall off from the straight line relationship.

A few experimental curves (Graph D) serve to illustrate the action, while curve (2) of graph F shows the input-output curve resultant with such a control. Over the range in which the control is operative, the average slope of the curve now is $\frac{7\frac{1}{2} + 20}{-54 + 20} = \frac{27\frac{1}{2}}{34} = .8$ Although there is still a slight concavity (due to the Eg - Gm characteristics of the controlled tube) theintensity of the control action has been much reduced and the control gives a nearly straight input-output curve over a 34 D.B. range. (-54 - -20).

The double control arrangement shown in fig.(7) provides a practical means for obtaining an input-output curve

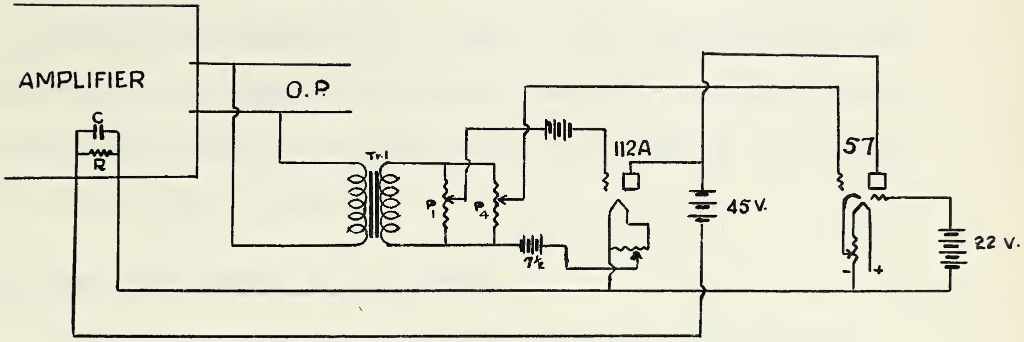


FIG.

which flattens off at any desired output level. (This gives an added safety valve action to prevent overload peaks.) The plate circuits of the two tubes, a 112A and a 57, are connected in parallel so that the current through R is the sum of their plate currents. Their grid circuits however have separate bias supplies so that their cut-off points maybe independently adjusted. From the curves of graph C, it is noted that a small grid voltage change produces a much greater plate current variation in the 57 than in the 112A. By operating P_4 at a higher setting than P_1 this difference is emphasized. If now the 112A is operated just beyond cut-off and the bias of the 57 is adjusted so that it does not become operative until the amplifier output has reached the desired maximum, we shall have normal automatic control action over the working range and beyond this a very sharp control action which will effect-

ively limit the output signal from the amplifier. Curve 3, Graph F is an example of such action obtained by using the circuit of fig. (7)

Because the parameter 'a' is fixed by the structure of the controlled tube, any change in the shape of the input-output curve must be effected through the rectifier and the above results are indicative of what may be expected.

The 'Power' and 'Range' of the Control.

The two other properties affecting the shape of the control curves are the 'power' and the range of the control. The power, which expresses the decibels reduction for a given DB. output depends upon the amplification of the control circuit. It can be increased by the use of a 57 tube in place of the 112A, or should this not prove sufficient, by amplifying the D.C. control voltage by means of a direct current amplifier. A better way perhaps than this last is to amplify the output voltage with another stage of amplification before applying it to the rectifier. Care must be taken however to prevent audio-frequency feed-back resulting from the high amplification of the signal.

The range of the control can be extended downward to lower input values by increasing the power of the control as mentioned above and by using a rectifier with a sharp cut-off. From this last standpoint a diode or copper-oxide rectifier or even a grid detection triode would give better results than the plate detection rectifier used. The limit to the range of the control in the upward direction is reached when the signal voltage swings the rectifier grid positive

or the control voltage across R reaches the value of the plate supply battery E_B . Both of these limits maybe extended by merely increasing both Eg_2 and E_B. In the case at hand neither of these limits was reached. The control curves (graph B) were not extended further upwards beyond the working range of the amplifier because of the experimental difficulty of obtaining sufficiently large inputs from the signal generator used. One curve however (80) was extended slightly to show the trend.

Distortion due to the Control

(a) Frequency distortion

An examination of the control circuit shows an almost complete absence of frequency discriminating elements. Transformer T_{r1} and condenser C are the only possibilities. Modern commercial transformers can be built with a frequency characteristic flat from 30 to 10,000 cycles, banishing concern in that direction. The condenser C functions as a by-pass to signal voltage variations in the plate circuit of the rectifier. It has a reactance of only 1200 ohms at the lowest audio note amplified (30 cycles). This is negligble compared with the 200,000 ohm resistor which it shunts, so this second possibility of frequency discrimination maybe dismissed.

The control does however vary* the plate resistance of the controlled tube T_1. Ordinarily in a transformer coupled circuit this

*Terman. Fig. 166

would alter the frequency characteristics of the amplifier but in this case the transformer primary is shunted with a 6000 ohm resistor so that any change in the relatively high value of R_p (800,000 ohms min.) is of no significance.

(b) Amplitude distortion.

The cause of amplitude distortion is non-linearity of a circuit element. The only change occuring in the amplifier operation due to the control action is the grid bias variation of T_1. The $Eg - I_P$ characteristic of a variable-mu tube is inherently curved, but at no point is this curvature sharp (Graph A). Normal operation (no control) takes place on a relatively straight portion of the curve ($Eg = -1.6$) but during a very loud passage the control may increase Eg to as much as -8 volts bringing the operation onto the curved portion. The amount of amplitude distortion then introduced will depend upon the grid voltage swing on this tube. Vacuum tube voltmeter measurements and calculations both give a probable maximum swing of .25 volts. With this small swing it becomes impossible to calculate with any degree of accuracy the very small percentage of second harmonic distortion introduced. It is of interest though to note that with the comparatively large swing of 1 volt (corresponding to an output of 12 D.B. above the normal maximum output of the amplifier) the distortion varies from 0 - 5% depending on the portion

of the curve over which operation occurs[1]. With a swing of 4 volts this would reach 10% in the worst case, indicating that while distortion is negligble at the maximum voltage actually applied, it would become serious[2] at larger voltages. Fortunately the maximum grid voltage applied to the first tube is in most studio installations very much less than that occuring in this case. Because of the low gain of this particular amplifier it is necessary to feed from the mixer as large an average signal as the microphones and record pick-ups will furnish, if the output level is to be maintained at that required by the transmitter. With the more usual three stage amplifiers having a gain 20 to 30 decibels higher, the imput to the first tube is correspondingly reduced and the problem of amplitude distortion does not exist. However the above does serve to indicate the inadvisability of using the control on any stage other than the first.

1. For example: for a 1 volt swing at $E_g = -2$ (from Graph A)

$$\% \text{ harm dist.} = \frac{\dfrac{I\ max - I\ min}{2} - I_0}{I\ max. - I\ min} = \frac{\dfrac{7.0-5.9}{2} - 6.4}{1.1}$$

$$= 4.5\%$$

For a 1 volt swing at $E_g = -6$

$$\text{Harm. dist.} = \frac{2.925 - 2.92}{.45} = 1\%$$

2. Frank Massa, Permissable Amplitude Distortion of Speech in an Audio Reproducing System, Proc. I.R.E. May, 1933, shows that the permissable amplitude distortion varies with the frequency range. He gives 5% for an amplifier with a 14000 cycle range and as high as 12% when the range is restricted to 5000 cycles. High Fidelity Systems require less than 5%.

(c) Phase Distortion

The problem of phase distortion is usually dismissed with the statement that it is of little importance in audio apparatus. The reason for this lies in the nature of phase distortion[1] and the characteristics of the ear. As far as it is possible to separate the effects of phase distortion from those of amplitude distortion, the former represents the change in wave shape due to a change in the phase relations of the different frequency components present in the received wave. Such a change will occur when the phase characteristic[1] is not a straight line thro' zero or some multiple of π.

But it is one of the fundamental laws[2] of hearing that the ear responds not to the wave shape of the combined frequencies but rather to the stimuli produced by the various individual frequency components such as are obtained on analysing the wave by Fourier Series. It follows then that the phase difference between two frequencies is unimportant so long as the difference in time delays is small. Since a change in phase of $\pi/3$ radians between a 500 cycle and a 1000 cycle note represents a time delay difference of only 1/6000 of a second, for the purposes of this investigation, the effects of phase distortion maybe ignored.

1. C.E. Lane, Phase Distortion in Telephone Apparatus, B.T.S. Monograph B 481, May, 1930.

2. Ohm's Acoustical Law. See van der Pol, A New Transformation in A.C. Theory, Proc. I.R.E. February, 1930.

(d) Transitional Distortion.

While the automatically controlled amplifier might be distortionless as far as the amplification of a constant signal is concerned, there still exists the possibility of distortion during those transition periods when the control is decreasing or increasing the amplifier gain. The only possible means for determining such would seem to be an oscillographic record of the wave form while the control is operating.

The Oscillograms.

To obtain such a record, a series of 'snaps'* of a 300 cycle wave were taken immediately before and at brief intervals after the control came into operation. A pure 300 cycle note**, synchronized with the 60 cycle power supply was fed through an attenuator network to the amplifier being controlled. The output of the amplifier was connected to the oscillograph, where because of synchronization with 60 cycle, a steady wave was observed. By cutting a 40 ohm shunt in or out of the attenuator network the signal input could be varied by about 8 decibels, this change in volume showing itself in a corresponding change in amplitude of the wave being observed. With the automatic gain control on and a signal input of say - 40 D.B., the shunt was removed by the

*See Appendix A.

**See Appendix B.

switching mechanism, increasing the input 8 D.B. The A.G.C. then became operative to reduce the increased output by a predetermined amount (depending on the settings of the control). Using the switching arrangement described in Appendix 1, instantaneous exposures of the wave shape were taken at approximately 1/40 of a second intervals after the volume increase with the results as shown in plate 1.

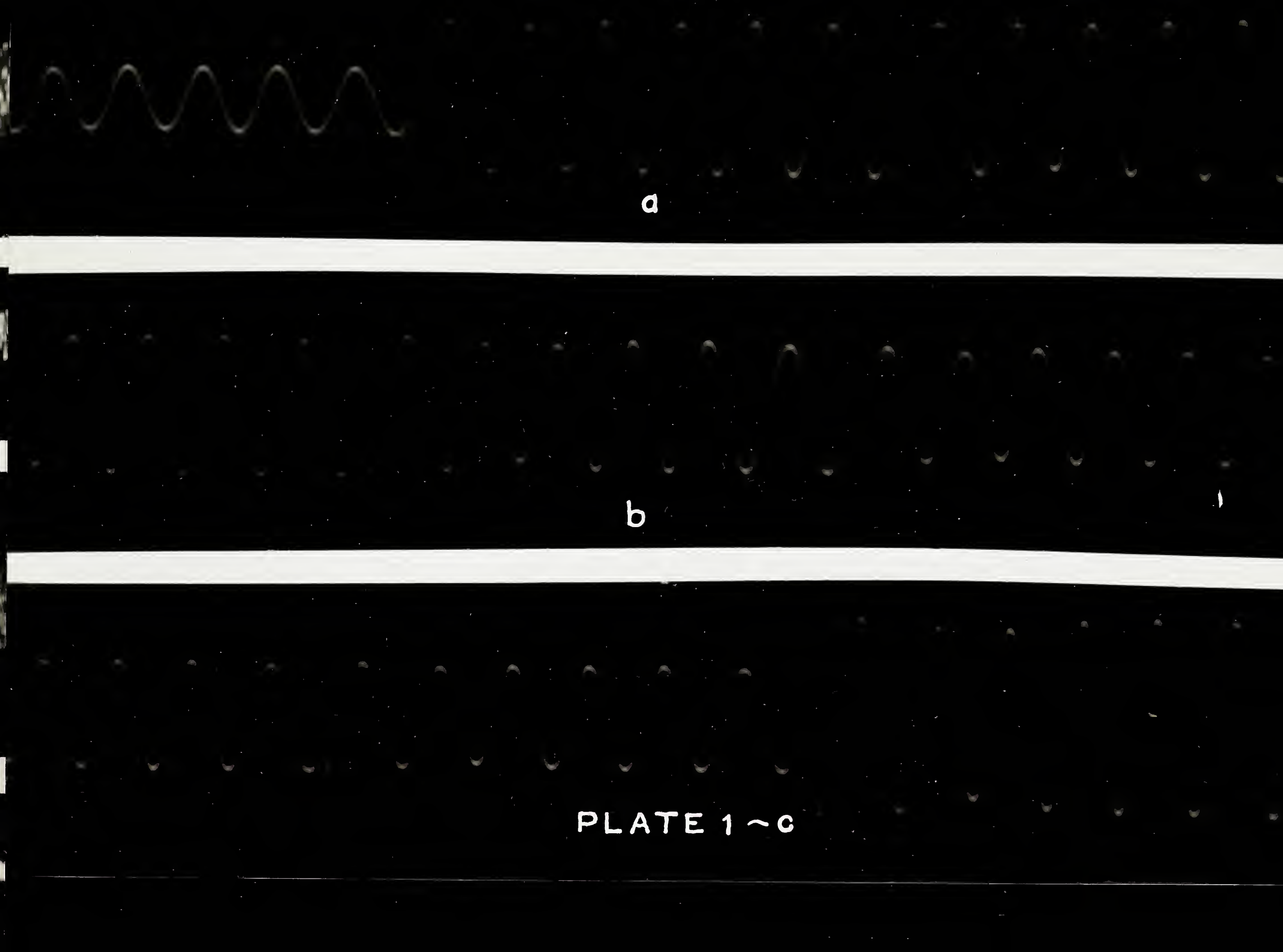


PLATE 1 ~c

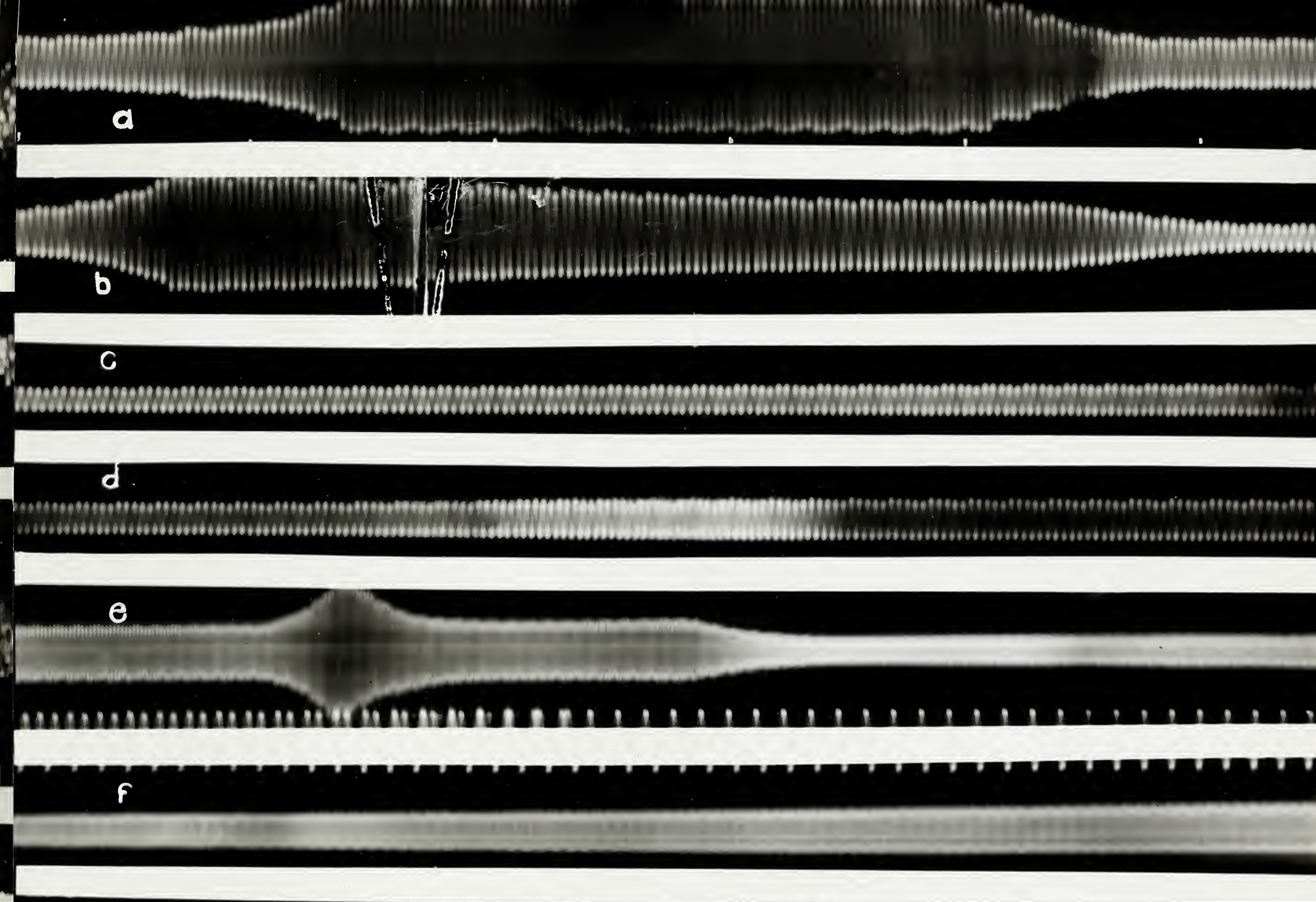


PLATE 2

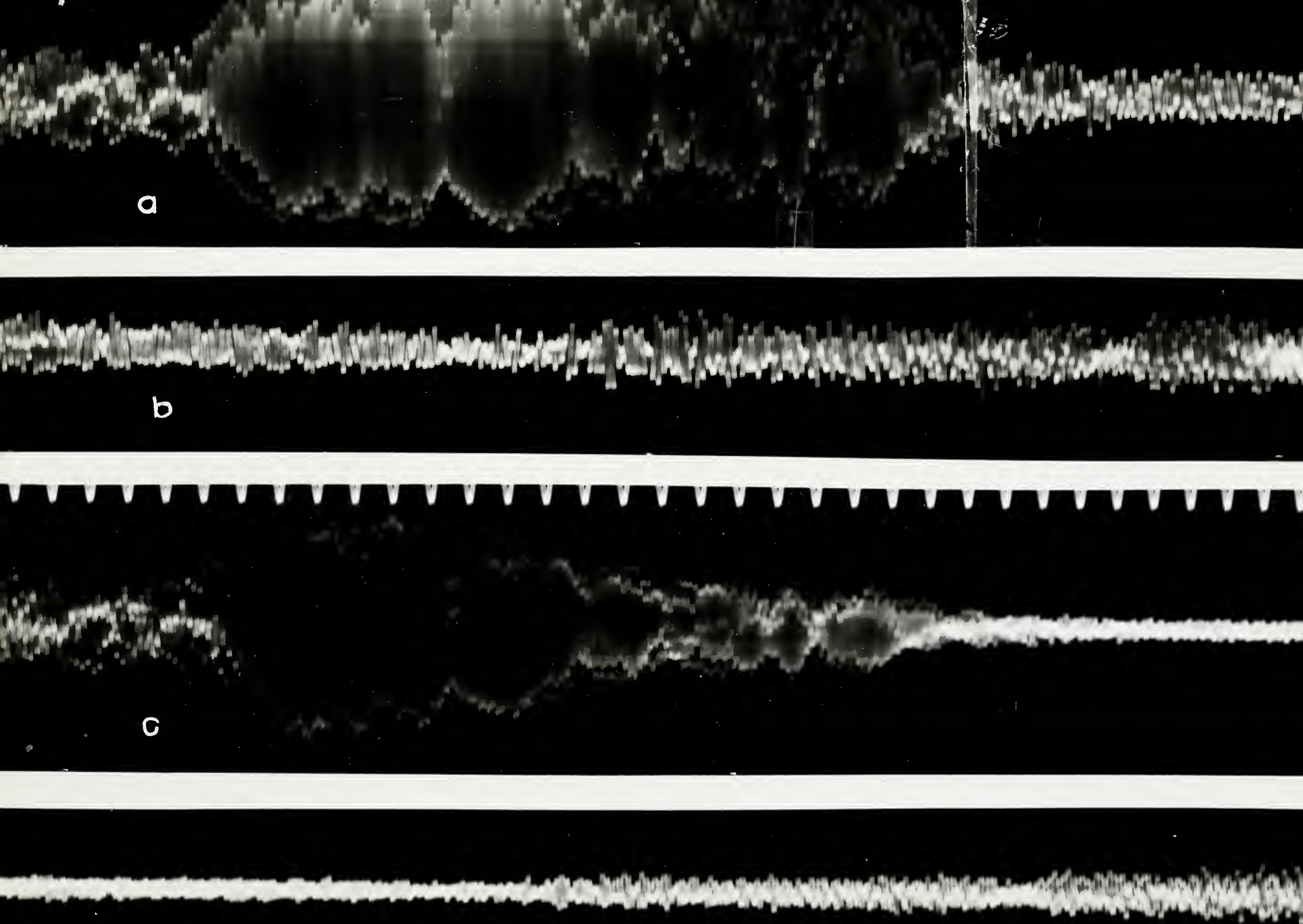


PLATE 3

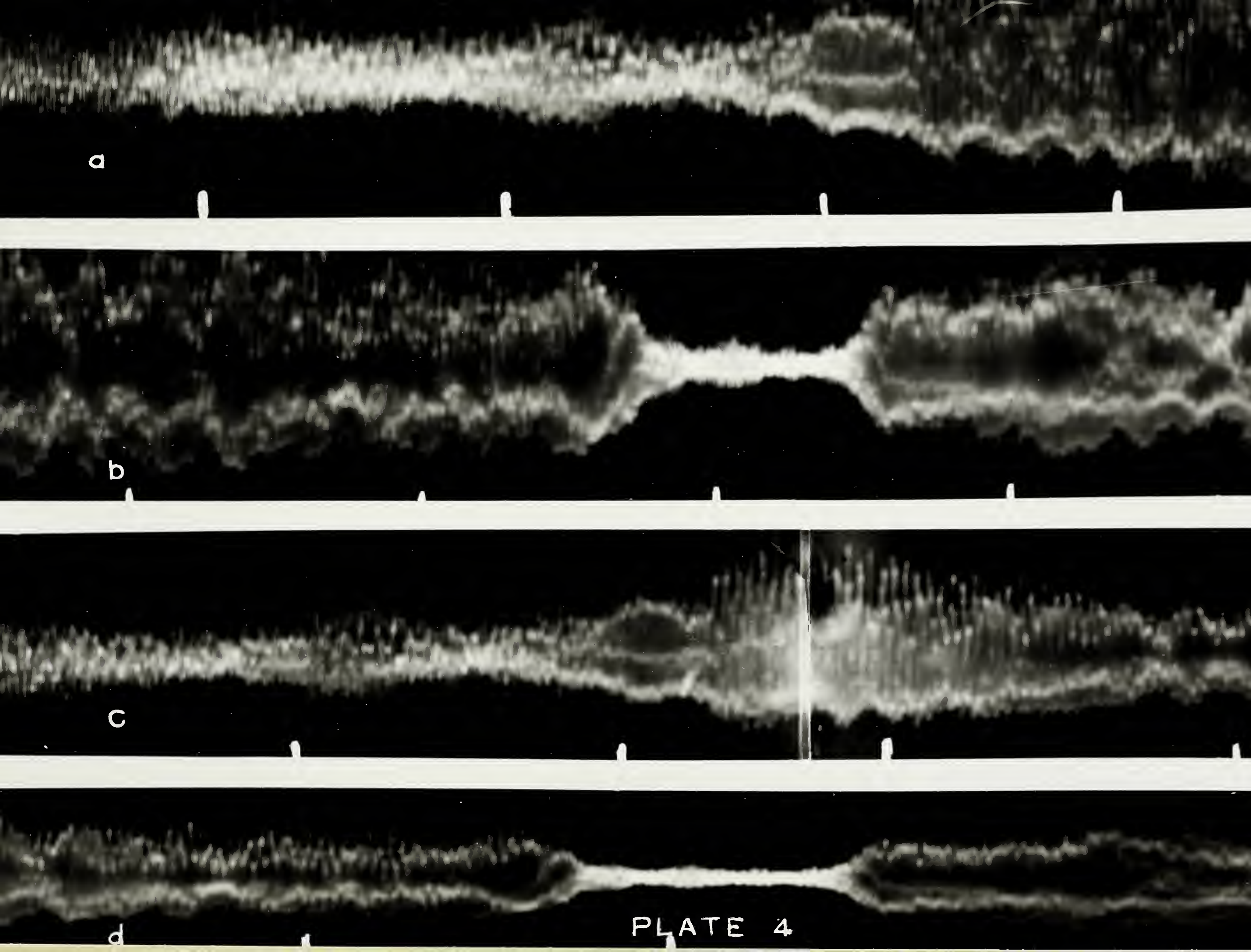


PLATE 4

Plate I

The first snap in plate I a shows the initial output of -4 D.B. The second and third snaps show the wave immediately after the input had been increased by 8 D.B. The remainder in b and c (except for the last) show the wave in successive 1/40 second intervals. There is thus portrayed a complete picture of the action over a period of approximately 6/40 seconds, during which time the gain reducing action has been completed. The last snap but one in c shows the final volume (-1 D.B.) at which the output was held by the control while the last picture shows for comparison the final increased volume (+ 4 D.B.) without the control.

So far as it is possible to detect it there is no distortion of the waveform due to the control. Each snap shows a pure sine[1] wave differing from the initial wave only in amplitude.

Plate 2

Plate 2 shows the same 300 cycle wave taken over a period of seconds with the continuous film attachment*. Strip 2(a) shows the note at - 6 D.B., increased to +4 D.B. by the manual control, held there for approximately 3/10 seconds and then decreased again by the same control. The tick marks indicate tenths of seconds. The

1. For an explanation of the slight variation in amplitude of the 6 cycles in each snap (especially noticeable in the last one) see Appendix B.

* Appendix C

slight 60 cycle modulation, previously mentioned, is more noticeable here because of the closeness of the adjacent cycles. The five 2D.B. steps of the manual control are readily discernable. Strips b,c, and d show the same cycle of events with the automatic control in operation. (Note that c and d are continuations of b.) The amplitude is increased as before by means of the manual control but instantly starts to decrease due to the automatic control and is held finally at a much smaller amplitude (about 0 D.B.). At the point where the volume is decreased manually (near the end of strip 2 b) the amplitude drops the full 8 D. B. and for the next second the control functions to gradually raise this level. (2 c and 2 d).

From this plate it is observed that while the control starts to operate immediately on a peak it requires about a 1/7 of a second to effect the major part (2/3) of the reduction and a full second to return the amplification to the maximum after the peak has passed. It is clearly evident too that there is no distortion of the wave form. The pure 300 cycle sine wave of constant amplitude becomes a pure sine wave whose amplitude decreases gradually according to an exponential[1] law Ae^{-x}.

1. Because this is the law followed by the charging of condenser C through the plate resistance R_p. Note that the expression for the wave $(B + Ae^{-t/CR})$ sin wt does not admit of being broken up by a Fourier analysis into a number of waves of differing frequencies. That is, no new frequencies are introduced.

Strips e and f show the same series of operations using a condenser in the time circuit having only $\frac{1}{4}$ the capacity of that used in b, c and d. In this case the major portion of the reduction occurs in about 1/30 of a second which (as the oscillogram shows) is about the same length of time as taken by the manual control to raise the volume.

The 'time' of the control however (i.e. to bring the volume back to normal) is still about one second as shown in 2e and 2 f and measured by the 60 cycle time wave. This was accomplished by using a larger resistance R so that the product CR was the same as previously.

Plate 3

Plate 3 (a and b) and (c and d) shows two similar portions from oscillograms taken of a soprano voice[1]. The particular portions shown are of a very sudden high peak, indicated by the abrupt increase in amplitude. a and b show the passage uncontrolled while c and d show the same passage with the automatic control operative. The time ticks are 1/60 seconds. It maybe observed that the increase in volume is so rapid that the wave reaches almost the same height with the control as without. However the control begins to act within 1/60 of a second (as gauged by the 60 cycle timing wave) to reduce the level. The control action in this case

1. Lotte Lehman singing "Er ist der Richtige" from Arabella. Parlophone Series, Record R.O. 20236

is quite marked and represents the limit of what might be expected in the form of very sudden volume changes. After being decreased the gain remains at this reduced value throughout the remainder of the passage shown although the peak itself is passed. This time delay in returning the amplification to its full value is essential if the naturalness of reproduction is to be maintained.

Plate 4

Plate 4, strips (a and b) and (c and d) are oscillograms of the voice of the baritone, Feodor Chaliapin in the "Song of the Volga Boatmen" (Victor Record 6822 - A). The passage shown is the last upward swing at the end of the first crescendo. The ticks indicate fifths of seconds so we are viewing the sound waves occuring in an interval of less than two seconds. The individual peaks are quite visible and the complex nature of sound becomes readily apparent. The dark passages occuring within the envelope are due to the rapidity with which the spot of light was required to traverse these portions. The beam width was narrowed slightly and this plate lacks the clarity and definition of plate 3.

Strips (a and b) show the passage uncontrolled while (c and d) show the same passage automatically controlled. Tick no. 2 in 4 a corresponds to tick no. 1 in 4 c. The difference in amplitude between the beginnings of strips a and c represents the extent of the controlling action already operative. As the volume increases

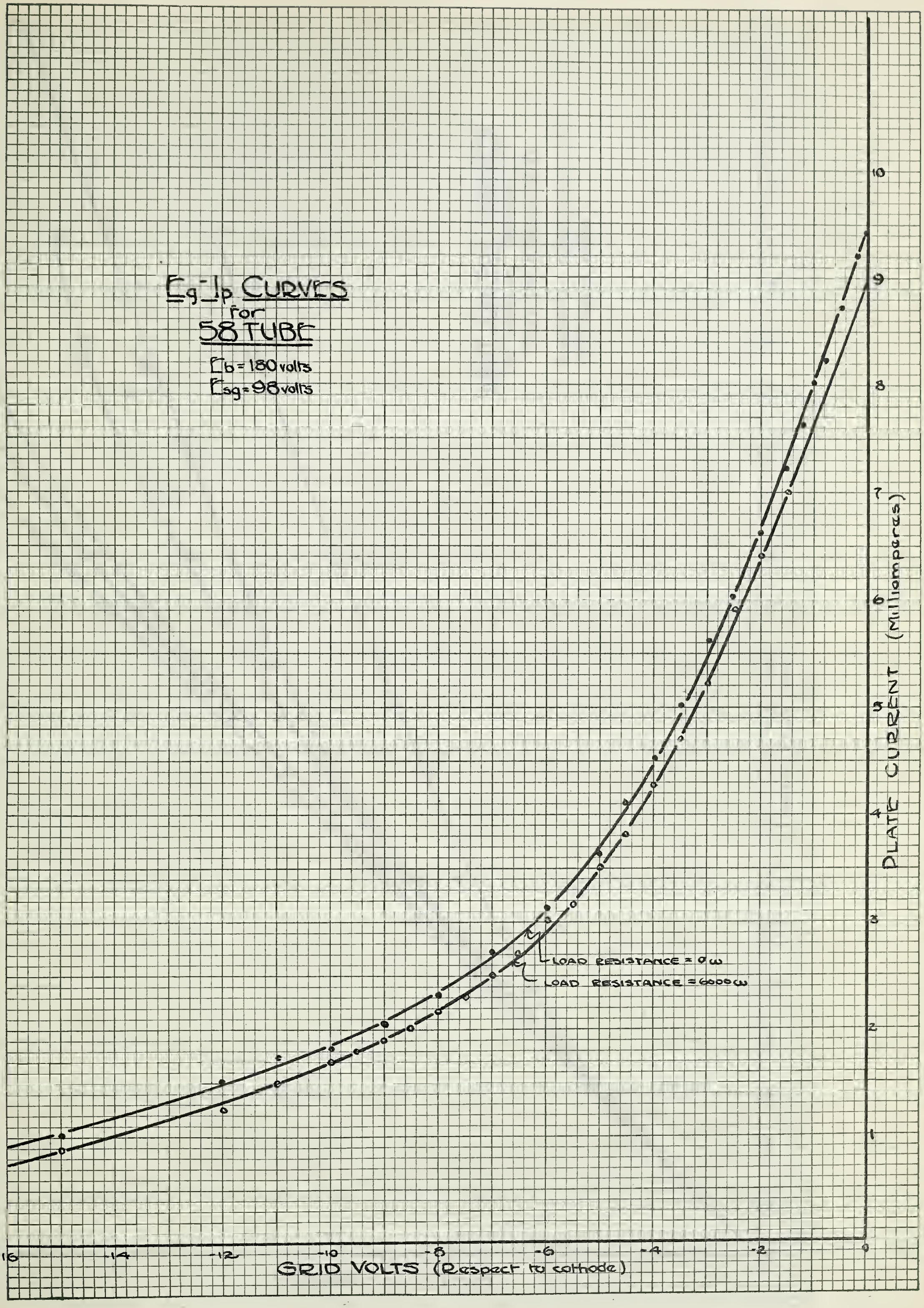
still further at tick 3 in (a), (tick 2 in c), there is a further reduction of gain by the control as shown occuring between ticks 3 and 4, strip c. Comparing d with b shows that the gain remains reduced throughout the rest of the loud passage shown*.

The oscillograms have shown very clearly the exact nature of the control action. There is no change of wave shape discernable (Plate 1), but merely a gradual increase or decrease in the amplitude of the wave envelope. (Plates 2,3,4). This is the same action as that produced by the manual control (Plate 2a) except that the automatic control has the advantages of being more gradual (and therefore less noticeable) and more accurate, the amount of reduction or increase of gain bearing a definite relation to the output volume. The reductions of gain ordinarily encountered are not nearly so drastic as would appear from plates 3 and 4. These are special instances, extreme cases of very sharp crescendos, selected to show the operation of the control under the most severe conditions. Moreover the relative amplitudes of the envelopes are functions of the voltage** ratios of the signal output, and a re-

* The tracings on (c and d) are spread out more than those on (a and b) due to a slight difference in film speeds.

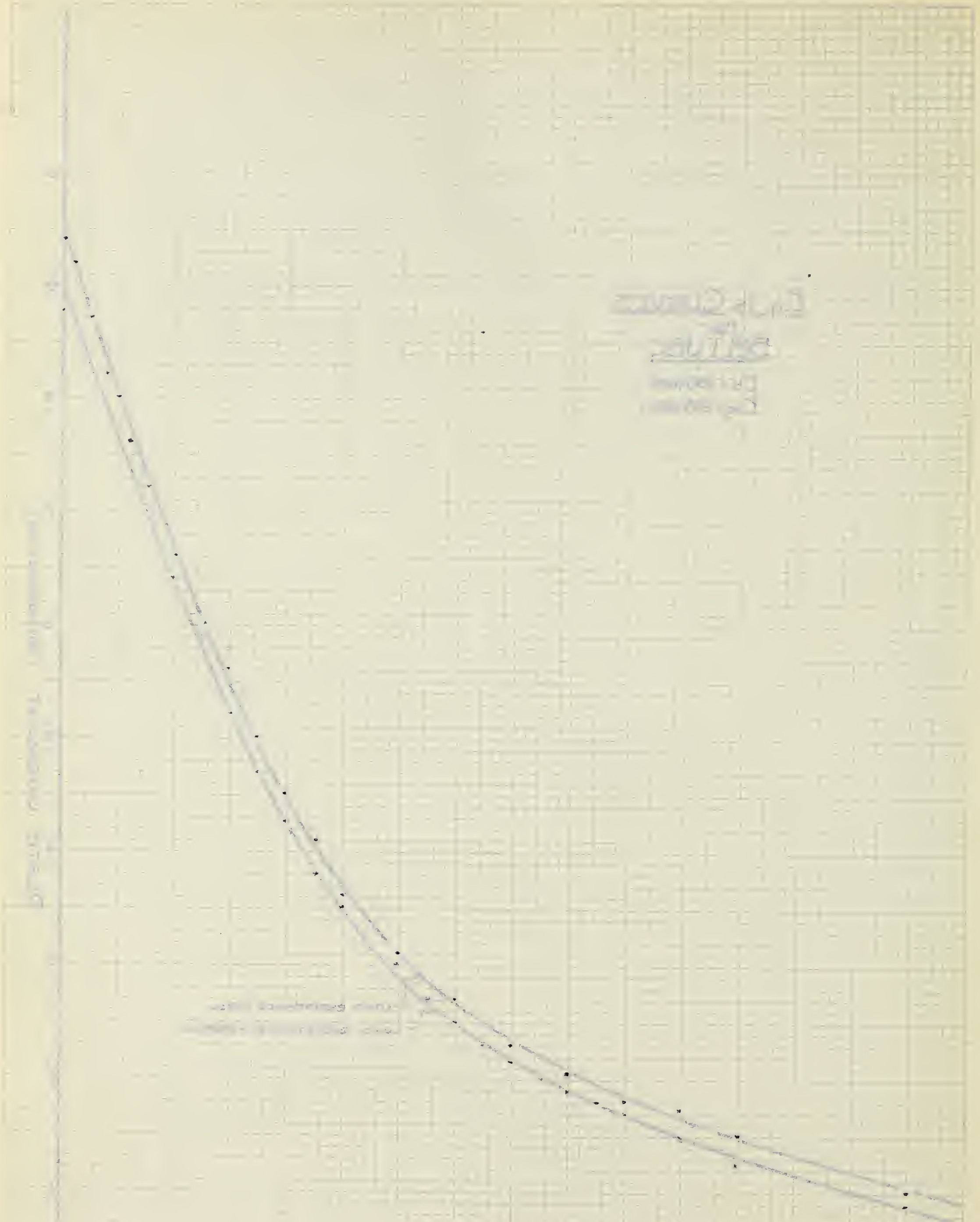
** Actually the beam deflections appeared to be more nearly proportional to the power output ($voltage^2$). If this were so, a reduction of 6 D.B. in output would reduce the amplitude of the envelopeto $\frac{1}{4}$ its former value.

duction of gain of 6 D.B. (comparatively small in a passage having a range of 30 to 40 decibels) will reduce the envelope amplitude to one half its former value. Under the more usual circumstances a passage of music or a song will increase or decrease in volume gradually over the comparatively long period of 1 or 2 seconds and here the control action will be correspondingly gradual - so gradual as to be almost indiscernable on the oscillograms.

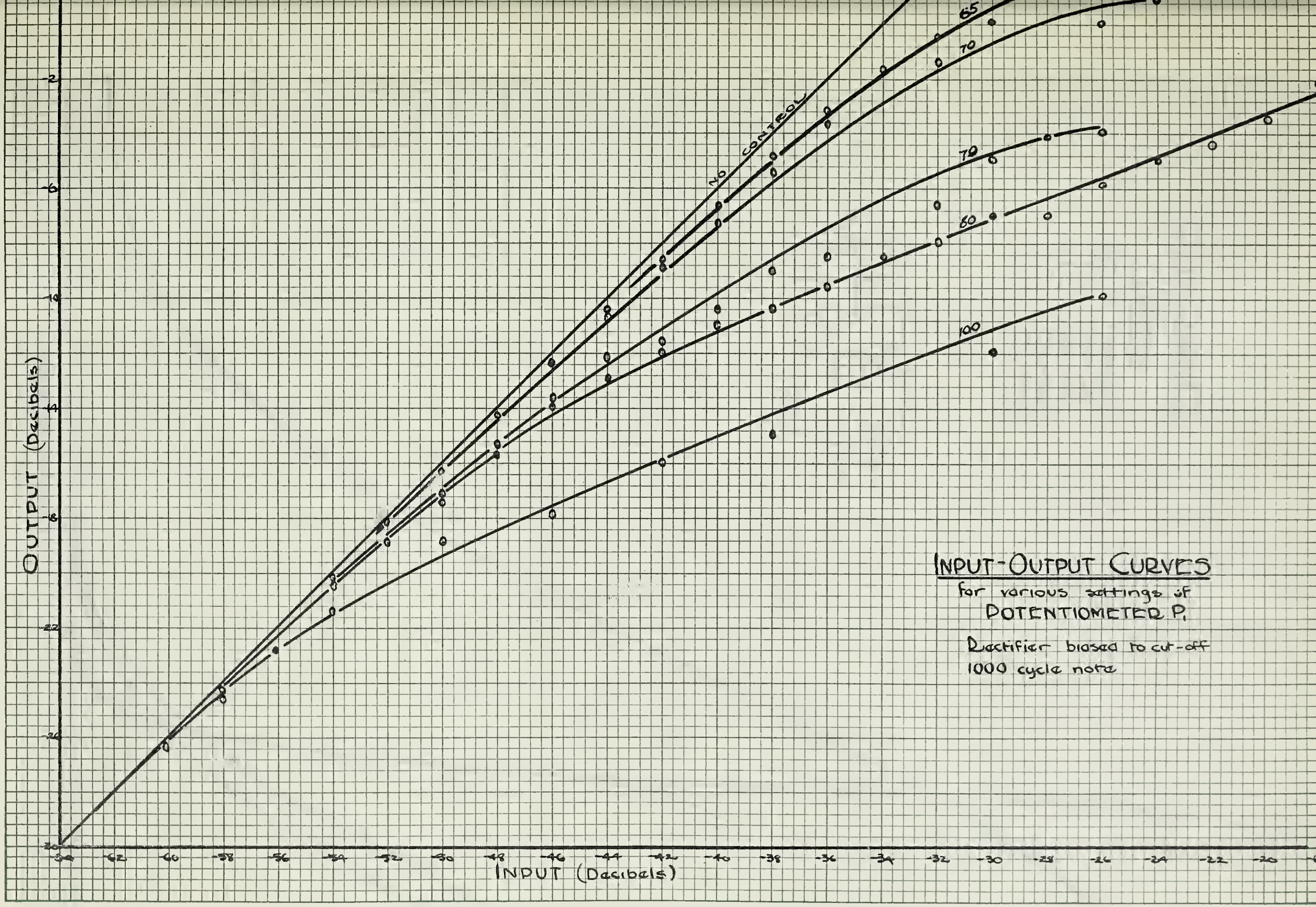


Eg-Ip CURVES
for
58 TUBE
Eb = 180 volts
Esg = 98 volts
LOAD RESISTANCE = 0 ω
LOAD RESISTANCE = 6000 ω
PLATE CURRENT (Milliamperes)
GRID VOLTS (Respect to cathode)
-16
-14
-12
-10
-8
-6
-4
-2
0
1
2
3
4
5
6
7
8
9
10

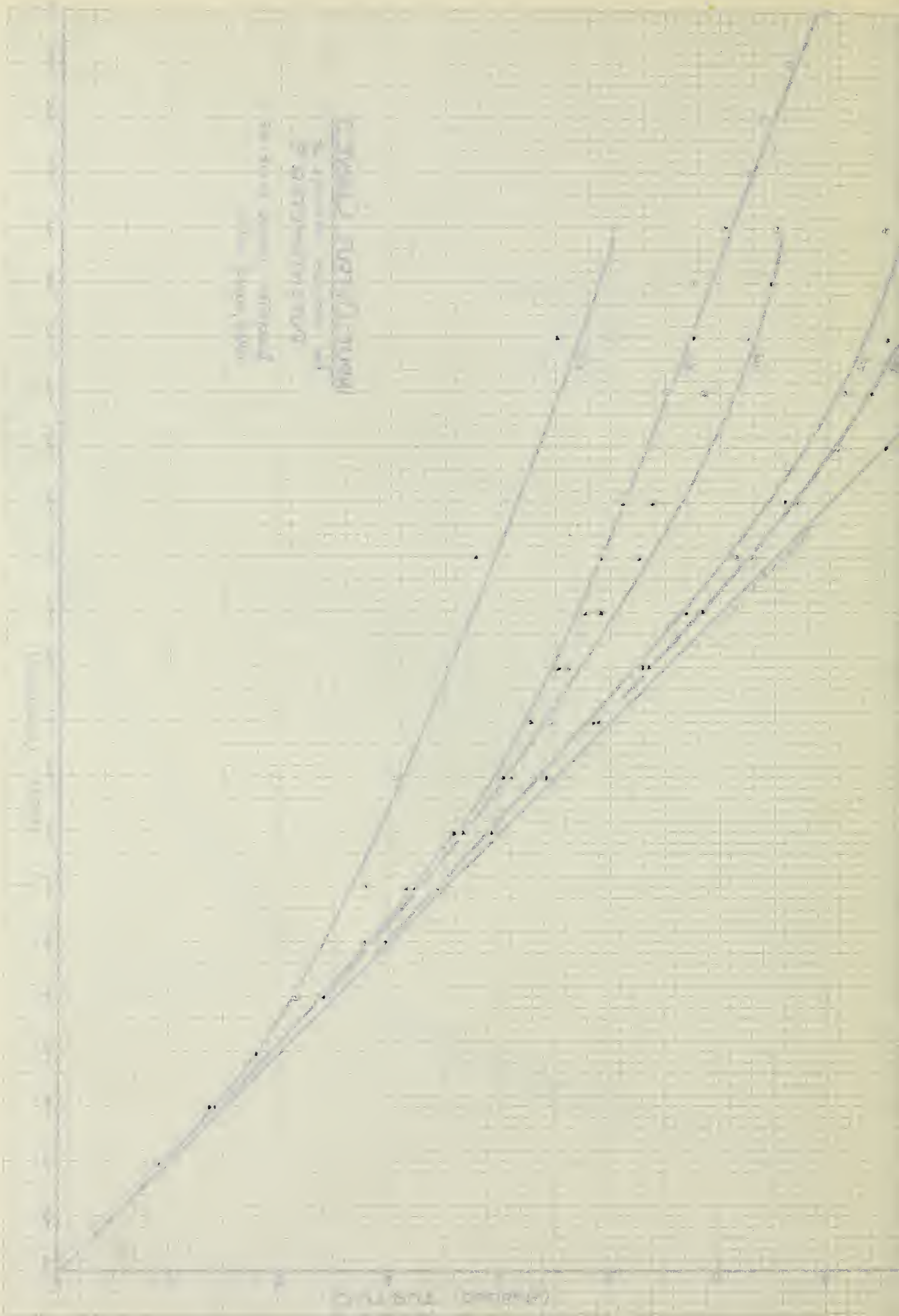
A

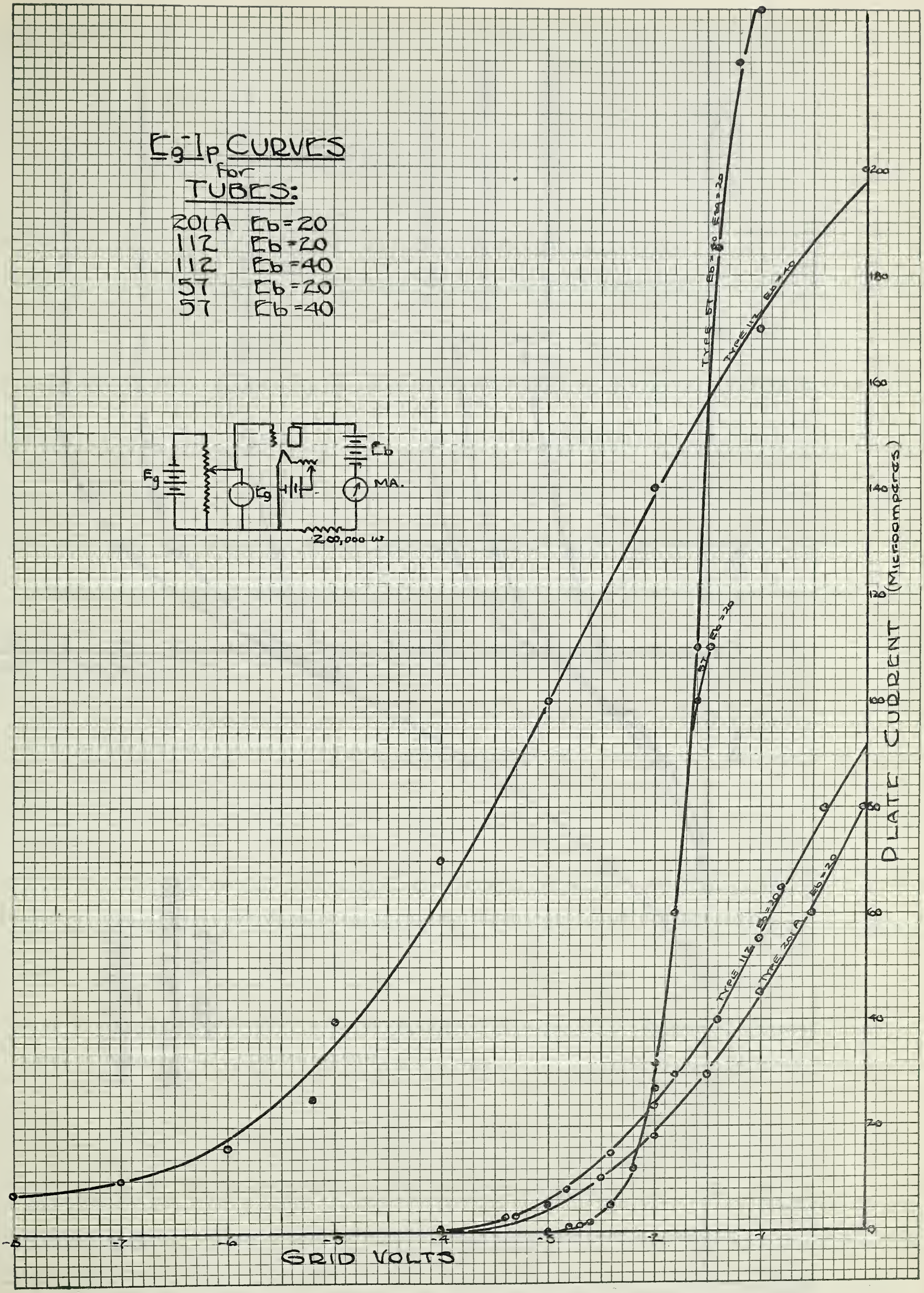


A


INPUT-OUTPUT CURVES
for various settings of
POTENTIOMETER P.
Rectifier biased to cut-off
1000 cycle note
NO CONTROL
65
70
70
80
100
OUTPUT (Decibels)
INPUT (Decibels)

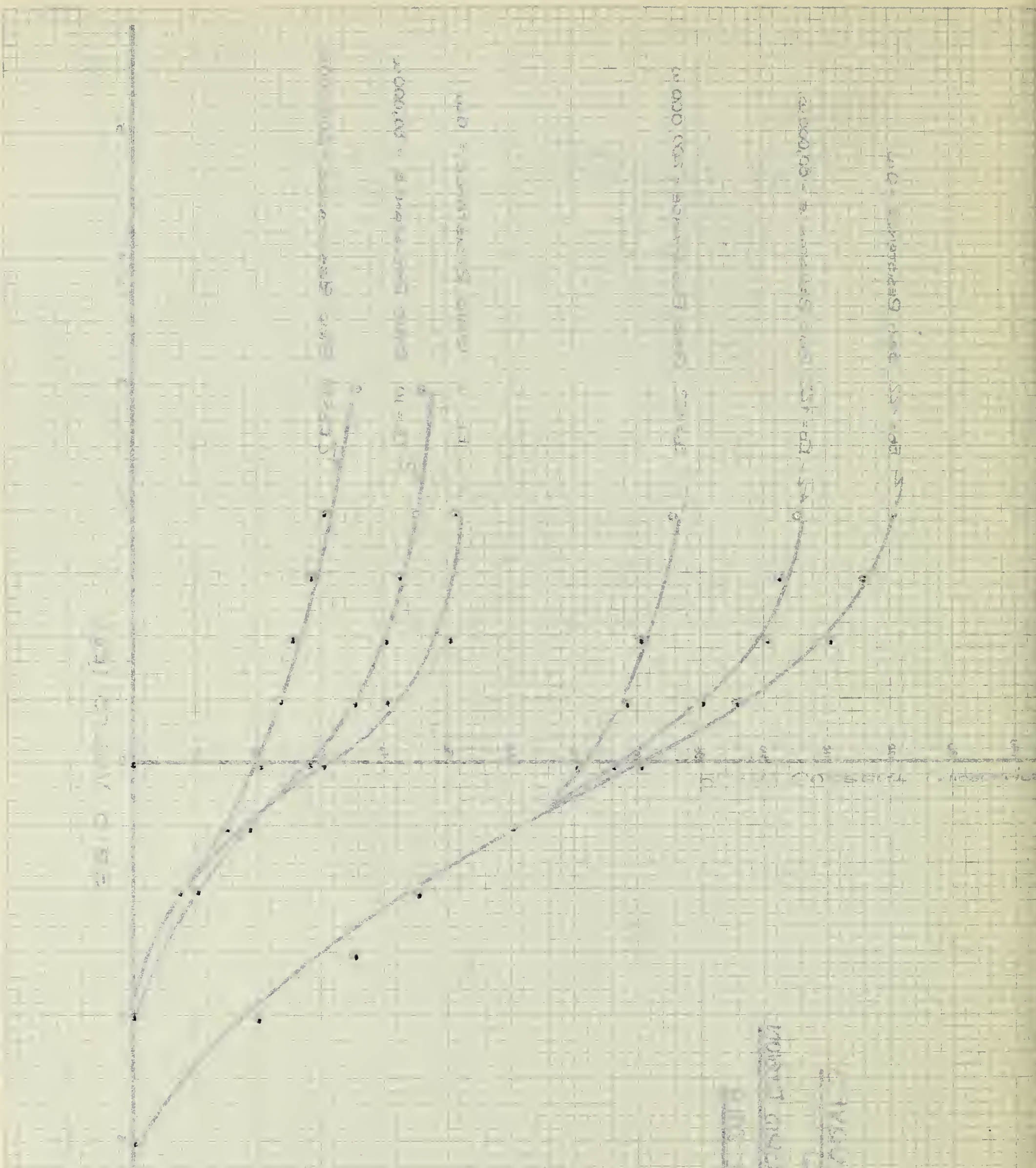
B

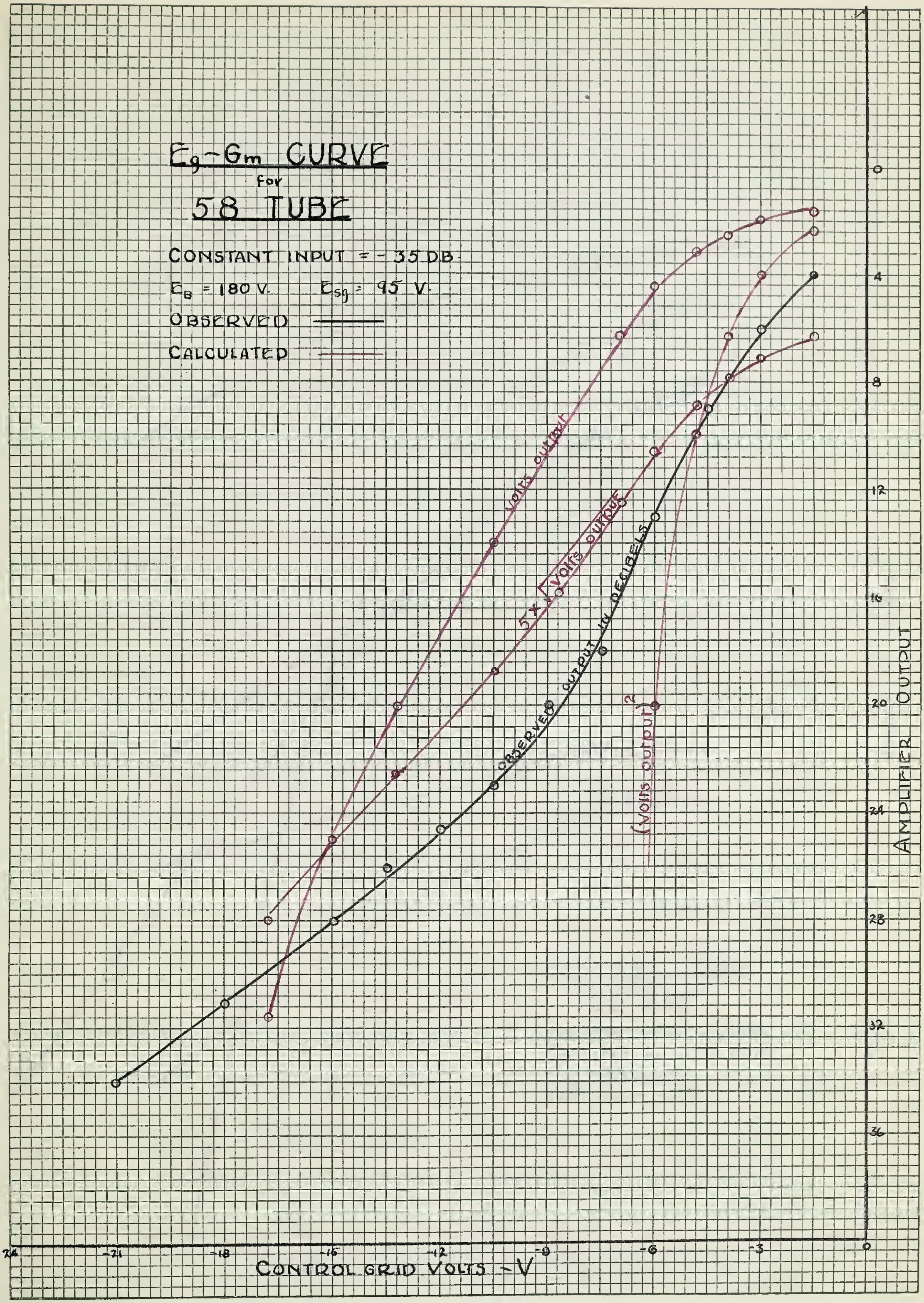




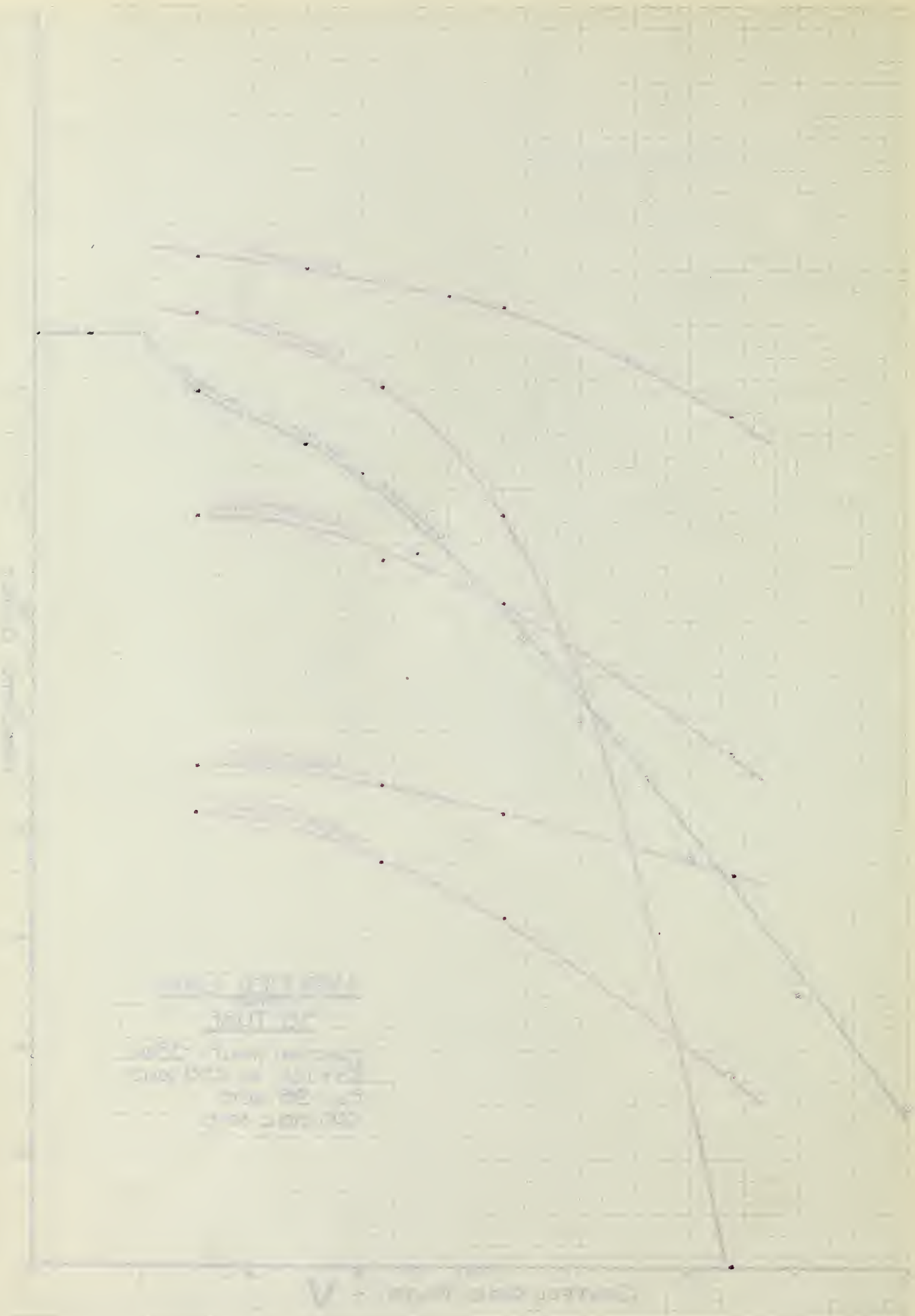
E_g-I_p CURVES for TUBES:
201A Eb=20
112 Eb=20
112 Eb=40
57 Eb=20
57 Eb=40
Eb
Eg
MA.
200,000 ω
TYPE 57 Eb=40
TYPE 112 Eb=40
57 Eb=20
TYPE 112 Eb=20
TYPE 201A Eb=20
PLATE CURRENT (Microamperes)
GRID VOLTS
-8
-7
-6
-5
-4
-3
-2
-1
0
20
40
60
80
100
120
140
160
180
200

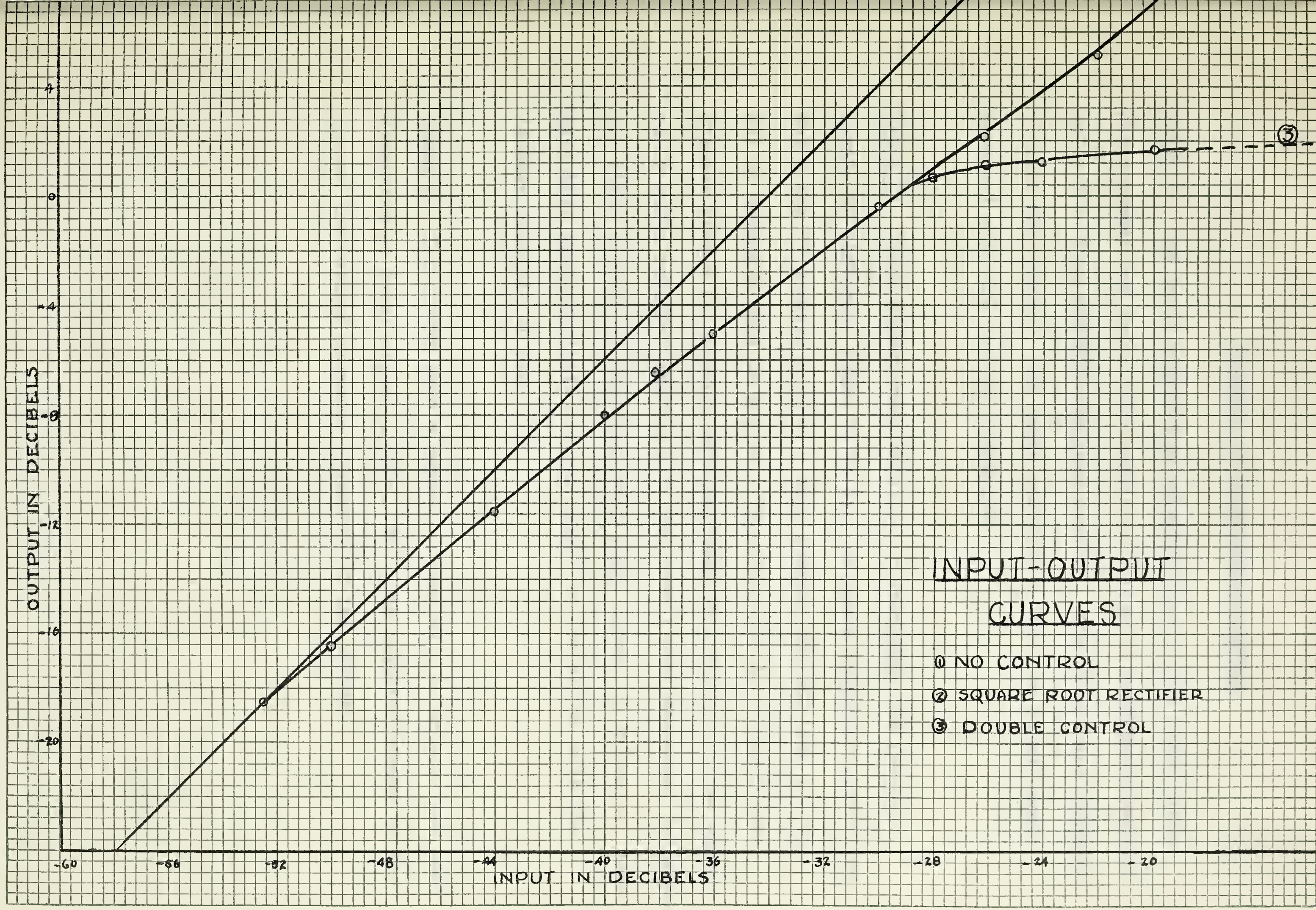
C




Eg-Gm CURVE
for
58 TUBE
CONSTANT INPUT = -35 DB.
EB = 180 V. Esg = 95 V.
OBSERVED
CALCULATED
Volts output
5 x √Volts output
OBSERVED OUTPUT IN DECIBELS
(Volts output)2
AMPLIFIER OUTPUT
CONTROL GRID VOLTS ~ V
-24
-21
-18
-15
-12
-9
-6
-3
0
0
4
8
12
16
20
24
28
32
36

E1




INPUT-OUTPUT
CURVES
① NO CONTROL
② SQUARE ROOT RECTIFIER
③ DOUBLE CONTROL
③
OUTPUT IN DECIBELS
INPUT IN DECIBELS
4
0
-4
-8
-12
-16
-20
-60
-56
-52
-48
-44
-40
-36
-32
-28
-24
-20

F

Comment on Experimental Curves

Graph B: The input signal was obtained from a 1000 cycle microphone hummer and fed to the amplifier through a resistance network and a G.R. Type 653,(200-ohm) gain control. The output was measured without the control, the input calculated, and the output again measured with the control operative.

Graph C: These curves were obtained to determine the relative merits of different tubes to be used as plate detection rectifiers. While the 57 appears to have a much sharper cut-off than 112 or 201 A, actually this is not so. For while the I_p of the 57 increases from 0 to 30 mils. with decrease of 1 volt grid bias against $2\frac{1}{4}$ volts required for the 112, the next 1 volt decrease, increases the plate current by the relatively large amount of 200 mils. However this characteristic becomes useful in connection with the 'double control' of fig. (7).

Graph D: The curves show a method of obtaining a 'square root law' detection at large signal inputs. The grid resistor serves to increase the desired downward concavity of the curves.

Graph E_1: To determine approximately the value of 'a' in the equation, --- Amplifier output $= \frac{k}{V^a}$ X amp. input. The observed output was expressed in volts^2, volts and volts$^{\frac{1}{2}}$. Linearity of the curve denotes a value of 1 for 1/a for that particular case. A small portion of the volts^1 curve shows linearity. Note that over this same range, the volts^2 curve is concave down while the volts$^{\frac{1}{2}}$ curve is concave up.

Graph E_2: shows the same curves as E_1 over a restricted range.

Graph F: Curve 2 illustrates the action of the root rectifier in changing the slope of the upper portion of the control curve. Note that it is approximately linear from - 54 to -20 D.B. Curve 3 shows the cut-off effect of the 'double control' circuit.

Studio Technique

The studio and operating technique with the control is similar to that evolved without its help. Microphoneplacement, relative positions of soloists and accompaniment, and so on, remain unchanged.

It was felt that because the large volumes consequent to having the microphone too close are partially masked by the control, the correct placement might be rendered difficult. Such is not the case. This is in part due to the method of operating with the control. The panel milliameter at j. 1 provides a convenient and accurate indication of the extent of the control action at any moment. It

is only necessary then instead of increasing the manual control until a certain swing is obtained on the program meter, to increase the gain up to the point where the automatic control can act upon the level as indicated by the swings of the milliameter. The manual control is thus adjusted for each individual selection as before (it is closed between selections in any event) but the continual controlling throughout the selection is done automatically. Should the operator err in his judgment and set his gain control too high, there is no unpleasant blasting to proclaim the fact to the entire listening audience; instead he merely observes that the control action is stronger than normal, and so reduces his gain - at his leisure.

The automatic control is particularly helpful in the production of dramatic programs. Here, three, four or even more channels are in use at once and it ordinarily becomes extremely difficult to keep the optimum balance between channel outputs and at the same time maintain the correct level to the transmitter. With the control relieving the operator of the latter duty, his work becomes simplified and its execution improved.

The Control on Detonations

Examination of theoscillograms reveals that the control requires from 1/10 to 1/5 seconds to complete its reduction of gain on a sudden peak. Is the control then of any use on those sudden sharp sounds which occur so often in plays (rifle shots, gongs, screams, etc.)? An oscillographic record of a rifle shot fired close to the microphone showed the main part of the report to be completed in 1/20 of a second. The program meter in this case indicated no reduction in level due to the control. However when the shot was fired some distance from the microphone, the control was effective in reducing its volume, this because of the time required for the sound to build up to its maximum in the room. Thus for indirect microphone pick-up (that is, where the main volume is due to wall reflections - source of sound more than two feet from the microphone) the control will act on any sound however sharp. Even with direct pick-up (source close to the microphone) most sounds such as gongs, buzzers, etc. are sufficiently slow in building up to their maximum to permit the control to operate. The effectiveness of the control on sharp reports is aided by the property of the ear of not recognizing sounds at the loudness corresponding to their intensity unless they are of at least .2 seconds duration. A pulse of given intensity lasting only .02 seconds appears to the ear to have the same loudness as a continuous note of 20 D.B. lower intensity. If a peak occurs suddenly then, it may momentarily reach

its uncontrolled height, but the control starts to operate within about 1/60 of a second, rapidly enough to prevent the sound reaching a loudness corresponding to the initial high intensity.

Full Automatic Control

Full automatic control, though not impossible to achieve, would be impracticable in operation. On the supposition that a 60 decibel range is to be reduced to 30 decibels (much as a scene is reduced on viewing through an inverted telescope) this would in practice mean increasing the gain on a very soft passage by 30 decibels. At this point of maximum gain all the in-between-selection noise would occur. Artist's breathing, the turning of music pages, and background record scratch would all be audible. Moreover the large reduction from this point of maximum gain required, for example, at the start of a loud orchestral selection would, more often than not, exceed the limits set by the maximum permissable decrement per unit time previously mentioned.

From these and other considerations it would seem that purely automatic control is not feasible. The control operator, with his human abilities to think, to reason, and to anticipate is still essential - even though his judgment be backed and his work made easy be an ever-ready assistant in the form of automatic control.

Conclusions

Although more complicated circuits such as that of figure (7) are required to obtain special forms of control action, the fundamental circuit of figure (4) provides a simple and effective control. It is easily built in to any amplifier circuit, the adjustments are few and simple, and it gives a distortionless, imperceptible control action. Such properties make it an important addition to any broadcast amplifier.

An investigation such as this cannot be undertaken without coming to some realization of the general spirit of cooperation and willingness to assist which prevails in the departments of the University. To Dr. Macleod, for supervision and advice during the course of the investigation, to Messrs. Cornish and Porteous, for assistance in constructing the continuous film equipment, and to Mr. Brown for use of the Department's photographic facilities, the author tenders his sincere thanks.

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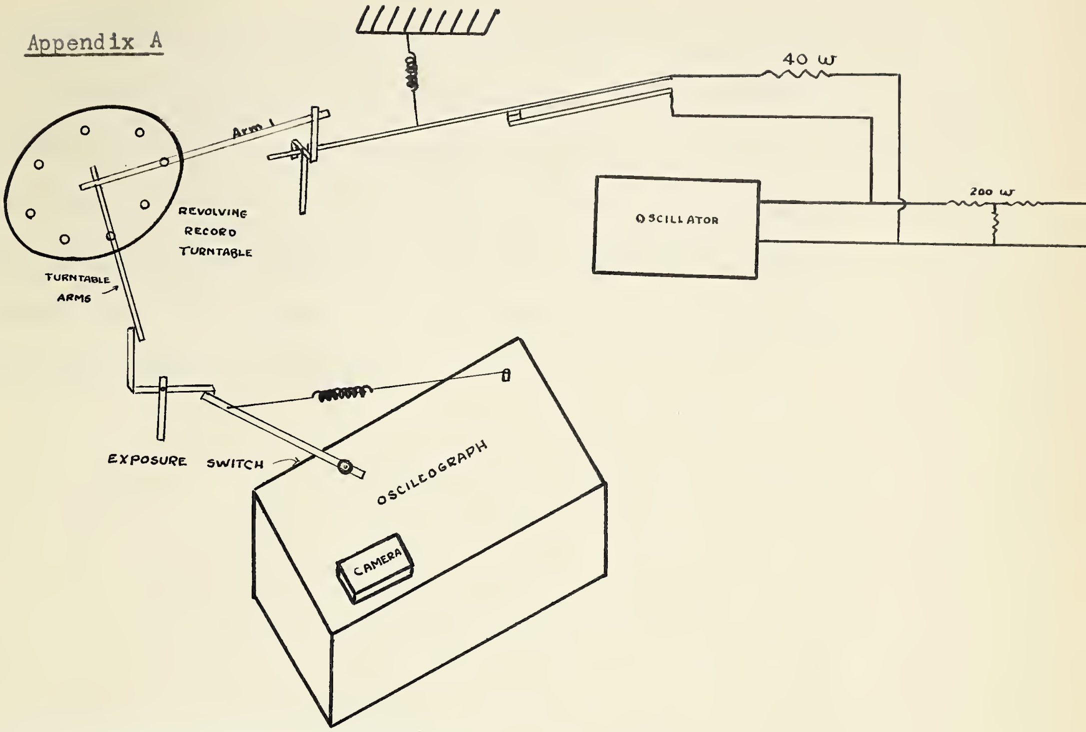
Appendix A



THE MECHANICAL SWITCHING ARRANGEMENT

The Still-Film Oscillograms

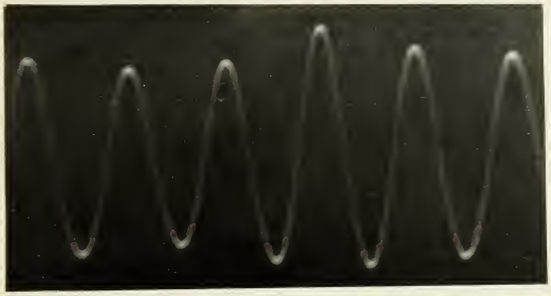
To obtain the 'snaps' of Plate 1, the above switching arrangement was used. The record turntable revolved at the constant speed of 80 r.p.m. It was connected to the motor by a clutch arrangement so that the motor could be already in rotation and the turntable brought up to speed almost instantly by throwing in the clutch. Varying time intervals between removal of the shunt by arm 1 and the snapping of the exposure switch on the oscillograph were obtained

by changing the angle between the turntable arms. The accuracy of the timing arrangement itself was estimated at one fiftieth of a second, but due to the internal switching mechanism of the oscillograph there is a time lag between the operation of the exposure switch and the actual exposure of the film, which lag may vary between 0 and 1/30 seconds so the accuracy of the system is only about one twentieth of a second.

Appendix B

The 300 Cycle Oscillator

While it was possible to generate a fairly pure 300 cycle note with an ordinary oscillator, for the purpose of viewing in the mechanical oscillograph it was desirable to have a note which was synchronized with the 60 cycle power supply, so giving a stationary wave shape. To obtain this a harmonic generator[1] circuit of the plate distortion type was built up and the fifth harmonic of 60 cycles amplified by the tuned circuit. This gave a 300 cycle note but there was also present the lower 60 cycle note, with the result that the wave form showed a 60 cycle envelope as illustrated (fig. 8).



Because it was desirable to have a 300 cycle wave of uniform amplitude, a series of experiments were carried out to determine a circuit which would give this. That of fig. (8a) was finally evolved.

1. Terman pg. 221.

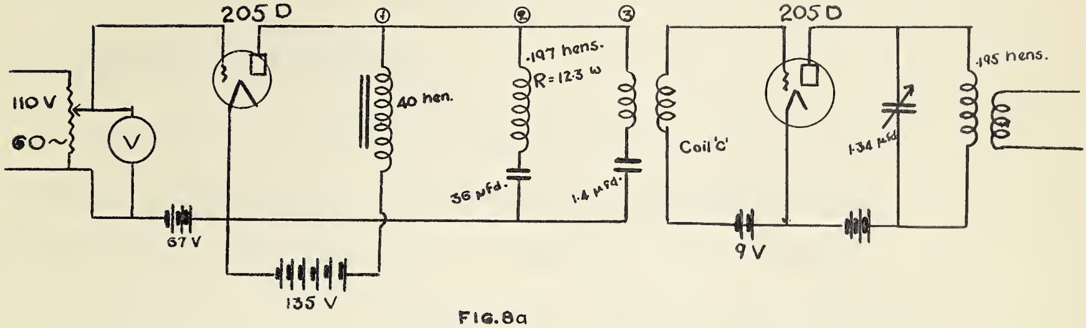


FIG.8a

Reactance in Ohms				
Branch	1	2	3	2 & 3 in ‖
At 60 ~	15000	12	1900	
At 300 ~	75000	353	-353	10,400

There are two circuits, tuned to 300 cycles so that there is high discrimination against the 60 cycle. The circuit branches 2 and 3 are parallel resonant at 300 cycles while branch 2 is series resonant at 60 cycles. There is an optimum A.C. grid voltage found by experiment to be 50 volts (effective).

The result was a relatively pure wave form seen in plate 1. A trace of the 60 cycle modulation is still visible in the last snap in 1-c.

Appendix C.

The Continuous Film Attachment

To observe the speech output of the amplifier over a period of seconds a continuous film attachment was constructed for the oscillograph. This consisted of a light-tight drum containing an aperture fitted with a sliding cover. Inside the drum revolves a cylindrical block of wood around which the film (SS - 120) is wrapped. The block has a length slightly in excess of the width of the film and a circumference equal to the length of the film (30"). The speed of revolution is determined by that of the driving motor (a variable speed Dumont) and the ratio of the gearing used (1:8 or 1:50). The time axis was removed from the oscillograph light beam by fitting a stationary mirror above the rocking mirror of the oscillograph. A vertical, single line trace was thus obtained which was spread out into a wave form by the movement of the film past the aperture.

The internal mechanism of the oscillograph was such that the operation of the exposure switch produced a single trace across the screen, the time of this trace being the same as the time required for the single forward motion of the rocking mirror, that is half the period of revolution of the oscillograph motor. By gearing the revolving block to the oscillograph motor with a 2:1 ratio so that the cylinder revolved once while the motor made $\frac{1}{2}$ revolution,

it became possible to ensure that a single trace ohly would appear on the film and that this trace would cover its entire length.

The advantages of this form of attachment over the double spool arrangement are its simplicity of construction, the wide range of film speeds obtainable (2/3' /sec. to 15'/sec.), the use of easily purchasable film (SS 120 panchromatic) and the constancy of film speed over the entire period of exposure (the cylinder is already revolving when exposure commences and no time is lost in comming up to speed). The length of exposure is of course limited to that of one film, 30", though if desired this could be increased to 60" by shifting the beam path from one side of the film to the other during one revolution thus making possible two traces on the single film.